SPACE TRANSPORT SYSTEM

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16 Abstract

Timely problems of modern space technology -- conversion from one-time use carrier rockets to multiple use space transport vehicles -- are outlined in the booklet. These systems permit regular maintenance of long-term orbital stations and automatic earth satellites, circumlunar orbital stations and lunar bases, and also facilitate organization of flights in the solar system and interplanetary expeditions. The booklet is intended for a broad range of readers interested in modern problems of cosmonautics.

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INTRODUCTION

Modern space management, in particular satellite management, is becoming ever more complex. Artificial earth satellites of various designation are being launched regularly into the most diverse orbits in the Soviet Union and United States. The Soviet Union is conducting systematic research by means of orbital stations of the "Salyut" type. Study of the Moon and circumlunar space by automatic vehicles is continuing. Seasons favorable for flights to Mars (one season lasts 1-2 months during an average cycle of 26 months) and to Venus (one monthly season every 19 months) are usually not missed by at least one of the countries -- the USSR or the United States. Investigation of Jupiter and the remote edges of the Solar System has begun.

Soviet carrier rockets have repeatedly inserted satellites into orbits whose equipment was developed by the combined efforts of scientists of the socialist countries and also satellites of India and France. A number of satellites of Great Britain, Italy, Canada, West Germany and so on and also satellites of the organization of West European countries -- the European Space Agency -- was launched by means of U.S. rockets. Great Britain, the Chinese People's Republic, France and Japan have inserted satellites into orbits by means of their own rockets.

According to data published in the United States, there were 3,629 objects, including 751 useful payloads in space and 2,781 auxiliary objects* in near-earth orbits and 53 useful payloads and 44 auxiliary objects in remote space on 5 October 1975. By the same date 4,723 objects, including 1,056 useful payloads and 3,667 auxiliary objects left orbit (entered the Earth's atmosphere or descended or fell to the Moon, Venus and Mars).

Artificial satellites of applied designation (communications satellites, meteorological and navigation satellites for investigation of natural resources, oceanographic and geodetic satellites and so on) began to play an ever increasing role in the economic life of various countries. When space

*Auxiliary objects are understood as the last stages of carrier rockets, protective nose cones and various fragments and parts inserted into orbit.

industry began to be developed, the sprouts of which we have already observed during the work of the crews of Soviet and American orbital stations, the population of our planet will sense the real benefit of space research to a greater degree than the benefit of aviation at present. Space economics will become an essential part of universal economics.

Hence ensues the necessity for seriously reducing the cost of space objects and space operations, the current high cost of which is generally known. First, transport vehicles must be developed which permit a sharp reduction in the cost of orbit insertion (for clarity -- into a low orbit located near the dense layers of the atmosphere -- an altitude on the order of 160-200 km) of 1 kg of payload and secondly, a reduction in the cost of the payload itself.

Here are some data on the cost of American carrier rockets. The "Scout" rocket (eight launches per year) costs 1.3 million dollars according to the "pre-inflationary" rate of exchange of 1972 and the expenditures for its launch and maintenance comprise 1.2 million dollars. Various modifications of the widely utilized "Thor-Delta" rockets cost from 3.1 to 3.9 million dollars, while expenditures for launch and maintenance cost 1.6 million dollars. The cost for other rockets are as follows: the "Atlas-Centaur" -- 10.1 and 3.1 million; the "Atlas-Centaur-Bjoerner-2" -- 10.7 and 3.1; "Titan-3B Centaur" -- 12.0 and 5.0; "Titan-3C" -- 15.6 and 7.7; "Titan-3D Centaur" -- 17.0 and 7.7; "Titan-3D Centaur-Bjoerner-2" -- 17.7 and 7.7 million dollars.

Many payloads cost considerably more than their own carrier rockets. For example, the cost of the American astronomical satellite "Copernicus" (launched on 21 August 1972 by the "Atlas Centaur" rocket) is 81.6 million dollars and that of the stationary satellite "ATC-6" is 120 million dollars.

The expenditures for every lunar expedition carried out by the American Apollo Program increased gradually due to the complication of the program and the length of the expedition and comprised approximately 450 million dollars for the last flights. This included the cost of the Saturn-5 carrier rocket -- 185 million dollars and of the Apollo spacecraft -- 95 million dollars. The cost of the entire Apollo Program, including six successful expeditions and one emergency expedition, with regard to the theoretical and experimental developments, development of different systems and preliminary experimental flights around the Earth and Moon is estimated at 25-26 billion dollars.*

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*Incidentally, the given data are quite comparable to the costs of aviation objects and are even inferior to them. For example, according to 1972 prices the cost of the Boeing-707 passenger aircraft was 10 million dollars, that of the Boeing-727 was 8.5, that of the Boeing-737 was 5.2, that of the Boeing-747 was 24 and that of the Concorde was 34.1 million dollars; a modern American multipurpose combat helicopter costs 1.4 million dollars.

The bane of space operations is not so much that they are carried out by means of extremely expensive equipment as the fact that it is totally unique and is used only once. This is true of both the space objects themselves and of the vehicles for delivering them into orbit or onto the surface of celestial bodies. Manned spacecraft are also mainly no exception: only part of the spacecraft (the recovery capsule) is returned to Earth and, although theoretically, may be used again. The recovery capsule of the "Vostok" spacecraft had a mass of 2.3 t with a launch mass of the "Vostok" carrier rocket of 400 t (Figure 1).

The current situation is such that an artificial Earth satellite after orbit insertion is transformed to a certain extent into "its own thing." The slightest malfunction may disable it forever and no repair of any kind is possible. The loss is tens of millions of rubles; a new satellite must be launched. Moreover, the same satellite could possibly be repaired by using a screwdriver or soldering iron! The simplest improvement in a design which includes replacement of some morally obsolete part by a new one is also not possible. The impossibility of repair requires that extremely high reliability of all satellite systems designed for prolonged operation be achieved and this adds considerably to their cost. Let us imagine that we are forced to scrap and acquire a new radio receiver, tape recorder, vacuum cleaner, bicycle, refrigerator or automobile at the first malfunction (even the smallest one). (True, cases are known when skillful control of an automatic spacecraft from Earth has made it possible to correct some damages to it. Thus, in one case it was possible to use the digging device of the American lunar vehicle "Surveyor-7," which was not designed for this purpose at all. But these exceptional cases only confirm the general rule.)

What can one say about carrier rockets which are completely lost upon fulfillment of their mission! The lower stages of carrier rockets (one or two) fall to the Earth's surface and are destroyed, while the stage which inserts the satellite into near-earth orbit itself rotates around the Earth for a more or less prolonged time, i.e., having retained its integrity (having lost only fuel), it is also transformed into a "thing into itself."

We have become accustomed to consider all this quite natural. But what would we think about the designer of a new, very fast comfortable air liner, doomed to total destruction immediately after the crew and passengers with their baggage left it after a successful landing! Imagine what tickets for such an aircraft would cost!

Solution of the problem of reducing the cost of space operations obviously includes development of multiple use vehicles for delivery of automatic and manned objects into orbits as distinguished from the existing single-use carrier rockets. Generally speaking there is nothing new in this idea itself. The return of cosmonauts to Earth in winged spacecraft ("rocket glider," as K. E. Tsiolkovskiy called it) or descent of the spacecraft on parachutes was usually provided in the investigations of the founders of cosmonautics K. E. Tsiolkovskiy, F. A. Tsander and Yu. V. Kondratyuk and

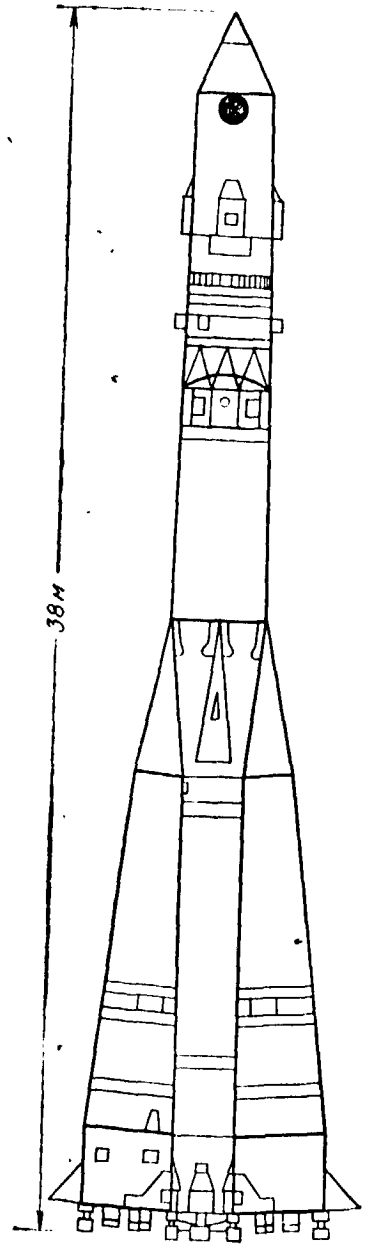

Figure 1. Diagram of Soviet "Vostok" Carrier Rocket (Length of 38 m). The black circle in the upper part is the hatch for entry into the recovery capsule

also of the well-known foreign specialists H. Obert, R. Eno-Peltri and others. Launch from the Earth was also sometimes considered as occurring in winged vehicles (F. A. Tsander used the term "superaviation" in this regard).

The years preceding the launch of the first Soviet artificial satellite and especially recent times (up to the end of the 1960's) had been characterized by an abundance of projects for winged flying vehicles designed for multiple use. And at the same time development of ever newer single-use carrier rockets continued and only these rockets were used in space research.

Although the cost of inserting a payload into a low orbit decreased from 80,000 to 5,000 dollars per kilogram in the United States during the period 1958-1972, it still remained extremely high. In the opinion of American specialists, the problem includes reduction of this cost by means of multimission transport spacecraft (MTKK) to at least 200 dollars.

It is important to emphasize that we are talking about the economic aspect of the matter, which logically ensues from the fact of the ever broader use of artificial Earth satellites. On the contrary, if it were determined that the number of future launches will not be too numerous, development of an MTKK requiring very large expenditures would not be feasible at least during some visible time interval, since existing rocket carriers would be adequate to solve all the problems.

Detailed consideration of economic problems is beyond the scope of this booklet. We will subsequently touch on the exceptionally scientific and technical aspects by assuming, not without justification, a rather high level of space operations in future years and their increasing role for universal economics.

As we shall see further, the problem of reducing the cost of payloads may also be resolved by using MTKK. The MTKK should become an element of a complex space transport system which would initially encompass near space, then the region of the Moon and later would emerge into interplanetary space. This is the main difference of the modern concept of a multiuse carrier from the "classical" winged vehicle, which was previously regarded mainly as a "space ferry" for communicating with a large manned artificial satellite.

ORBITAL AIRCRAFT

Evolution of the Idea of a Multimission Transport Spacecraft

The following capabilities of rescue and multimission of a transport vehicle which inserts an artificial satellite into a moderately high orbit (let us say not above 1,000 km above the Earth's surface) are theoretically conceivable. The lower stages of the carrier, which do not reach orbital velocity, descend on parachutes or in gliding flight (using wings). The upper stage, inserted into orbit simultaneously with the payload, is returned to the atmosphere by a slight thrust of a special retro-rocket and makes a gliding descent in it, accompanied by a horizontal landing similar to an ordinary aircraft.

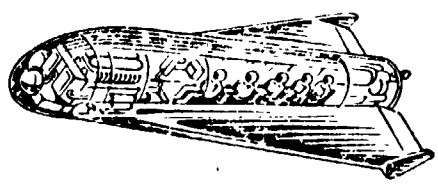

Figure 2. Project "Slomar"

The case of suborbital flight when the vehicle with a lift force not being able to essentially be inserted into orbit (and, consequently, not being a carrier vehicle) makes one or two revolutions around the Earth in a skipping flight, being multiply bounced from the dense layers of the atmosphere, is also possible. The project of a similar vehicle, called an "antibode bomber" with a range of 23,500 km, was proposed in 1944 by the German specialist E. Senger, and some foreign writers begin their story about development of the idea of a multiuse transport spacecraft with his idea.

New projects for multiuse carrier vehicles began to appear at the end of the 1940's. In 1952 W. von Braun advanced the project of a rocket with a launch mass of 7,000 t, all three stages of which were equipped with wings. It was planned to use several of these rockets to assemble a large orbital station at an altitude of 1,730 km. In 1960 the U.S. Air Force began investigation

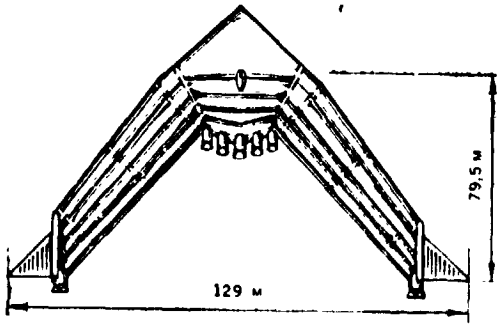

Figure 3. Project "Astroplane"

of the manned winged vehicle "Slomar" (Figure 2), capable of carrying five persons to an orbital station. The American project "Astroplane" (Figure 3) -- a single-stage vehicle using oxygen-hydrogen fuel, whose wings consisted of hydrogen tanks (a launch mass of 4,450 t, payload in low orbit of 200 t and landing mass of 331 t), is related to this same time period. Let us also note the more modest projects of 1964: "Astro" (Figure 4) -- a two-stage spacecraft (only the second stage is manned) with a launch mass of 400 t and payload of 10 t in an orbit at altitude of 550 km and "Astrorocket" -- a vehicle with a launch mass of 1,100 t and payload of 23 t at an orbital altitude of 500 km (each of the two stages, joined in parallel, has a delta wing). At the same time project "Dyna-Soar" -- a single-seat rocket glider inserted into orbit by the Titan-3C carrier rocket (Figure 5), was developed in great detail. The interesting English project of the "Mustard" spacecraft (Figure 6), consisting of three vehicles with delta-shaped support fuselages, is related to 1966.

Investigations of the problem of developing a single-stage vehicle with a jet engine were carried out during this period in the United States and great difficulties were encountered on this path. Nuclear engines had to be rejected because of the danger of returning nuclear reactors into the lower atmosphere and to Earth. Numerous flight experiments were carried out with models of hypersonic vehicles -- winged and with a supporting body, and also with the X-15 rocket aircraft, which, being launched from a bomber, developed a speed of 7,260 km/hr and reached an altitude of 108 km in one of its flights.

In 1968, on the eve of the beginning of the Apollo Lunar Program, the United States space agency NASA, planning operations in maintenance in future orbital stations, adopted a decision to develop a multimission transport spacecraft (MTKK). In January 1969 the first contracts were concluded with four companies for the principal investigation of MTKK projects. Other companies also participated in the competition. Projects related to 1970 and 1971, in which the booster stages are manned winged vehicles, approximately equal in length to the Boeing-747 airliner (approximately 70 m), are shown in Figures 7, 8 and 9. The variant in Figure 9 is characterized below by jettisonable hydrogen tanks in the orbital stage.

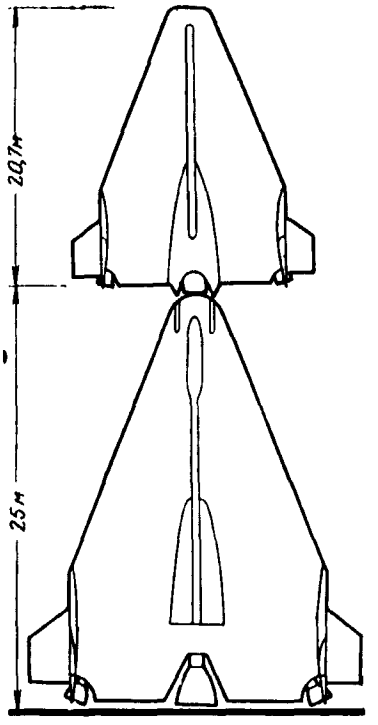

Figure 4. Project "Astro"

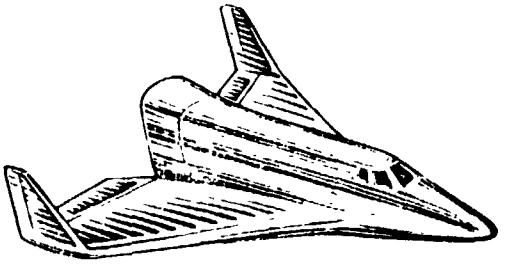

Figure 5. Project "Dyna-Soar"

The requirements on increasing the final payload of MTKK (already having assumed the distinct form of an orbital aircraft) increased as developments advanced and the requirement of maximum utilization of already existing technology was advanced simultaneously. It was decided in 1972 that the orbital stage should have a delta wing and large external fuel tank (the aircraft "sits" on it), in the design of which the experience of developing the second S-II stage of the Saturn-5 lunar rocket was utilized. The orbital stage should be joined either in series (Figure 10, a and b) or in parallel (Figure 10, c and d) to the booster stage, which has no lift force. The booster stage is two units connected by the sides to the external fuel

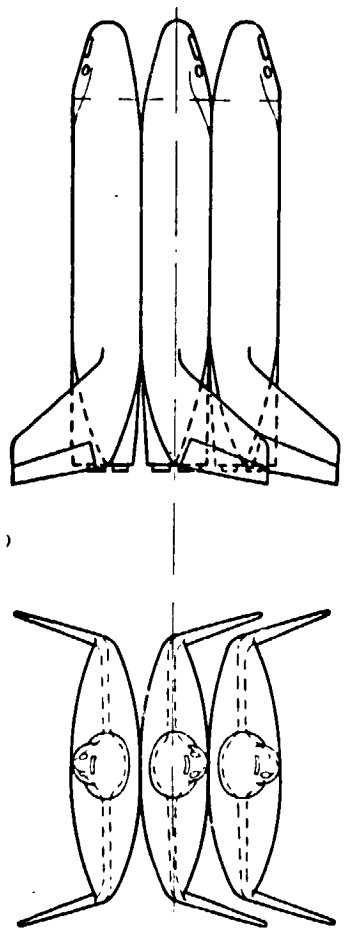

Figure 6. Project "Mustard" (Depicted in Two Planes)

tank (Figure 10), in most variants in parallel joining. The booster stage was based either on a liquid propellant rocket engine or on a solid propellant rocket engine, and recovery of the solid propellant rocket engine was initially not provided. On 15 March 1972 NASA selected the variant of the booster stage in the form of two parachute-recoverable solid propellant rocket engines (RDTT). Detailed design of the MTKK in the variant of Figure 10, d was begun.

Project "Spaceplane"

Let us consider in more detail the manned spacecraft which is called by different names in the literature: a multiuse transport spacecraft (MTKK), orbital aircraft and space aircraft. The official name "Spaceplane," which may be translated as "Cosmoplane," has recently been adopted in the United States. This name replaced the old name "shuttle" or "space shuttle," which

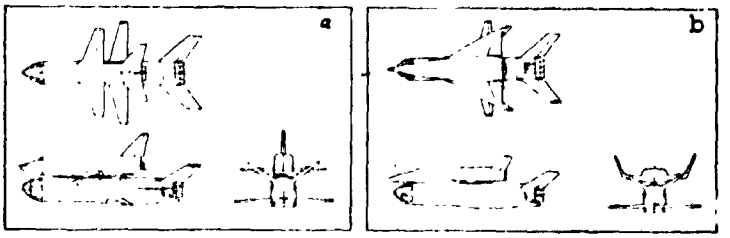

Figure 7. MTKK With Orbital Stage of Low (a) and High (b) Lateral Range (1970 Projects). The image is given in three planes

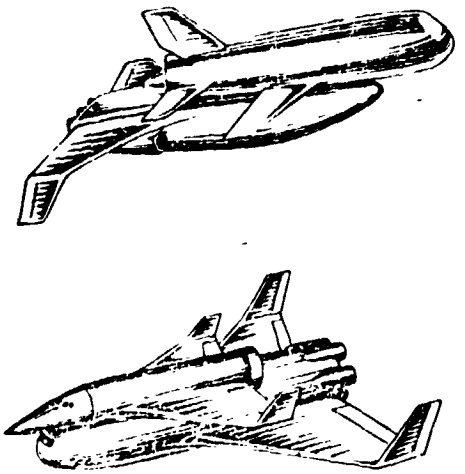

Figure 8. 1970 Projects of MTKK

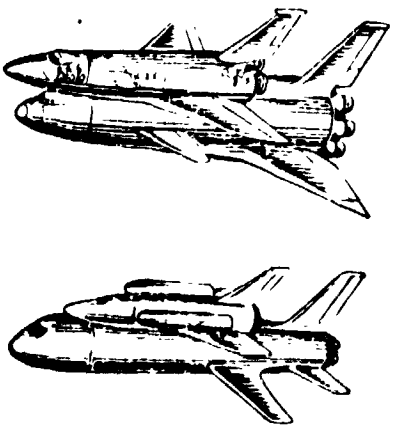

Figure 9. 1971 Projects of MTKK

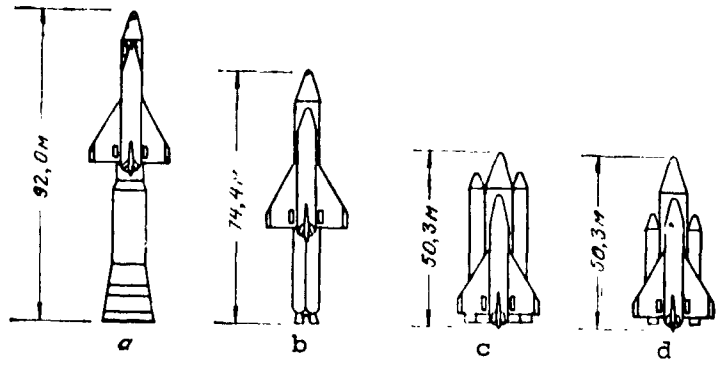

Figure 10. Variants of MTKK With Series (a and b) and Parallel (c and d) Joining of Stages: a and c -- the booster stage is based on a liquid propellant rocket engine; b and d -- this same stage consists of two RDTT. The dimensions of the external fuel tank are 5.6 x 33 m (a and b) and 7.1 x 37.6 m (c and d)

refers to the fact that the spacecraft is supposed to warp between orbit and the Earth like a shuttle.*

The orbital aircraft is the main space project of the United States after the Apollo program. The first flight of the "Spaceplane" will denote restoration of manned American flights, interrupted after completion of the Apollo Program (1972), the Skylab program (1973) and ASTP (1975).

The overall dimensions of the MTKK as a whole are indicated in Figure 11 and the overall dimensions of the orbital stage are shown in Figure 12.

Let us indicate the mass and energy characteristics of MTKK. The launch mass of the MTKK (without payload), according to data for the beginning of 1974, is equal to 1,814 t. The mass of the two RDTT is 1,056 t. The mass of the external tank containing a forward compartment with liquid oxygen and an aft compartment with liquid hydrogen is 740 t. The dry mass of the orbital stage is 68 t.

Payload data are as follows. Upon launch from Cape Canaveral, when the launch occurs precisely toward the east (orbital inclination of 28.5° -- the latitute of Cape Canaveral), the payload is 29.5 t in a circular orbit at altitude of 400 km; it is 11.3 t at an altitude of 400 km at an inclination of 53°; the circular orbit has an altitude of 550 km without a payload

*The given data correspond mainly to the status of development by the end of 1973 (especially the numerical parameters); slight changes are being introduced continuously into the development system (usually due to financial factors).

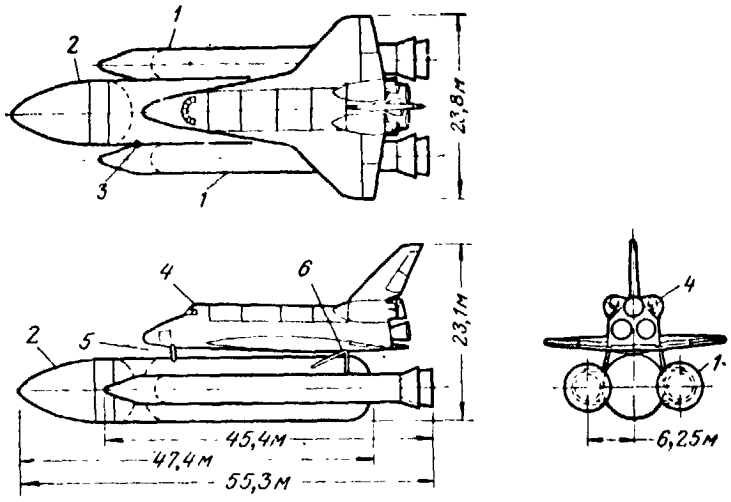

Figure 11. Diagram of MTKK (Shown in Three Planes): 1 -- RDTT of booster stage (diameter of 3.7 m); 2 -- external oxygen-hydrogen fuel tank of orbital stage (diameter of 8.4 m); 3 -- power unit for attaching RDTT to external tank; 4 -- orbital stage; 5 -- forward unit for attaching orbital stage to external tank; 6 -- aft securing unit

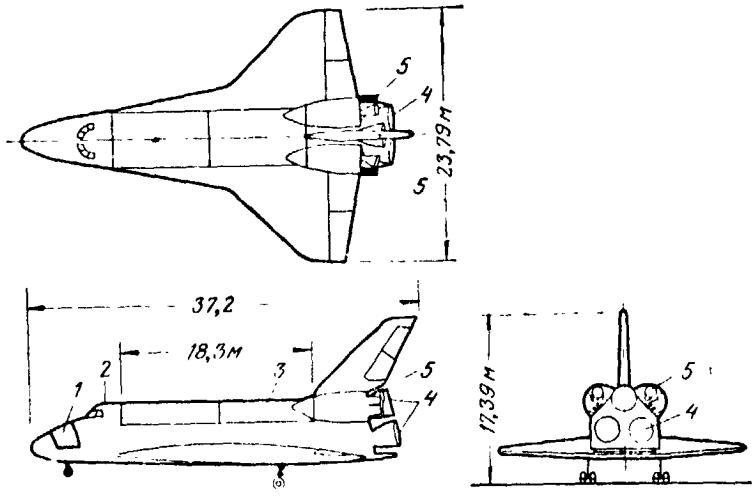

Figure 12. Diagram of Orbital Stage of MTKK (in Three Planes): 1 -- forward unit of liquid propellant rocket orientation engine; 2 -- cockpit; 3 -- cargo compartment; 4 -- three sustainer ZhRD; 5 -- two aft units (gondolas) of orbital maneuvering and orientation ZhRD

and with launching toward the east. When launched toward the south from Vandenberg Air Force Base (the west coast of the United States)*: the payload is 18.2 t in a circular orbit at altitude of 275 km. The payload is placed in a special unpressurized cargo compartment 18.3 m long and 4.6 m in diameter (volume of 365 m^3). The crew members may enter it from the forward cockpit through an air lock chamber.

The energy characteristics of the MTKK may be improved if part of the cargo compartment is occupied by additional sets (up to 3) of fuel tanks for the orbital maneuvering liquid propellant rocket engine (ZhRD). An increase of the velocity characteristics by 152 m/s corresponds to each set. The MTKK may deliver 11.0 t to a circular orbit at altitude of 1,120 km with these three sets when launched in an easterly direction from Cape Canaveral or may be inserted into a 1,020-kilometer circular orbit with payload when launched to the south from Vandenberg Air Force Base. The mass of the payload returned from orbit to Earth is up to 14.5 t.

The total launch thrust of the two RDTT of the booster stage is 2,325 t. The three sustainer ZhRD of the orbital stage. which draw liquid oxygen and liquid hydrogen from the external fuel tank (a fuel reserve of 708 t) through pipelines, create a total thrust of 510 t at sea level (639 t in a vacuum) and have a specific impulse of 455 s. Gimbal suspensions permit them to rotate. Orbital maneuvering is provided by two ZhRD with a thrust of 2.7 t each at a specific impulse of 308 s. They operate on monomethyl hydrazine and nitrogen tetroxide. The fuel reserve inside the orbital stage (without additional tanks) corresponds to a velocity characteristic of 300 m/s at a payload of 29.5 t. The 40 attitude ZhRD (16 in the forward unit and 12 each in the two aft units) have a thrust of 400 kgf each and the other 6 have a thrust of 11.3 kgf each; they operate on the same type of fuel.

Let us consider the typical and of course the approximate diagram of MTKK operation. Individual operations will subsequently be denoted in parentheses by the figures corresponding to the positions in Figure 13.

The MTKK is launched (1) vertically with the two RDTT and three sustainer ZhRD operating simultaneously (total thrust of 2,835 t). A banking turn ("falling onto the back") and deviation from the vertical begin within 6 s (2). The empty RDTT bodies (3) separate within approximately 125 s at an altitude of 43 km at a velocity of 1,440 m/s and angle of arrival of 28° and descend (4-6) into the Pacific Ocean on parachutes (an impact velocity of 24 m/s is permissible) and are then towed (7) to the launch-landing complex for repeated (up to 100 times) utilization (8). The sustainer ZhRD are switched off within 490 s after launch, when approximately 30 m/s remains until orbit insertion, the empty external fuel tank is separated and the orbital maneuvering ZhRD (9) is immediately fired. The tank falls into a remote region

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*Launches from Cape Canaveral permit inclinations from 28.5 to 57°, while launches from Vandenberg Air Force Base permit inclinations from 56 to 104°.

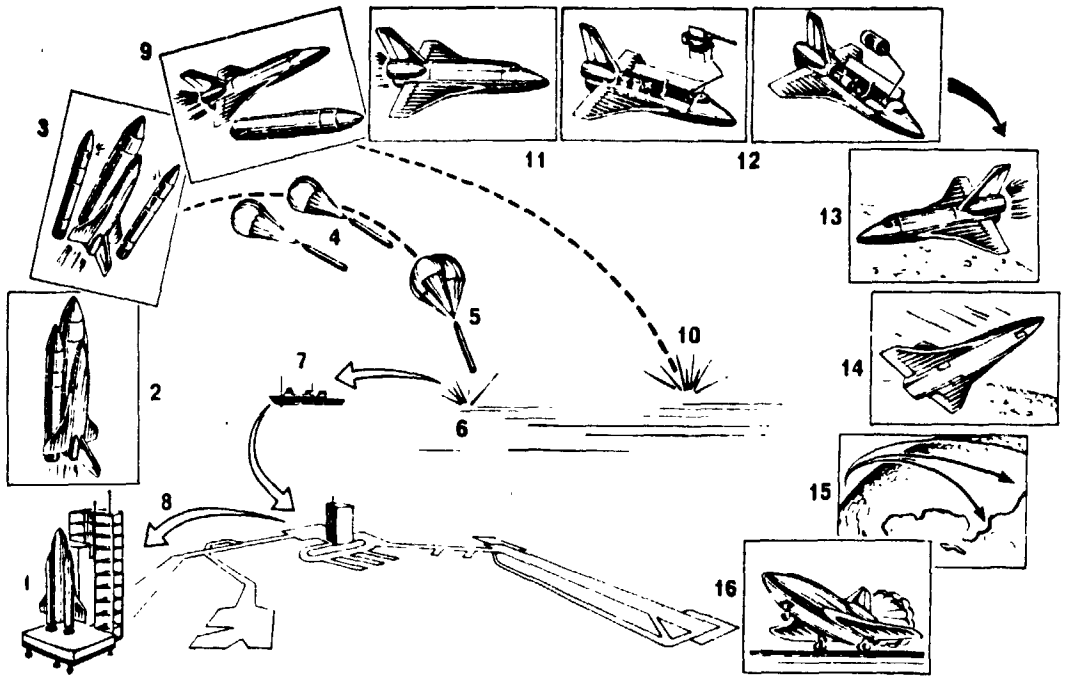

Figure 13. Diagram of MTKK Operations

of the Indian Ocean and is lost (10).* The orbital stage changes to an elliptical transfer orbit (11) at 120 km within 700 s after launch. Firing at apogee then changes the MTKK to a circular orbit. The orbital operations (12) continue from several hours to 1 month. Prior to descent from orbit, the orbital stage turns with its tail forward and the orbital maneuvering ZhRD fires a braking pulse (13). The stage is again turned and reentry into the atmosphere occurs at a large angle of attack (14). Lateral maneuvering is then accomplished within a strip 2,000 km wide 15). The final descent leg begins at an altitude of 21 km at an approximately constant speed (560-610 km/hr). The landing approach begins within 3.5 min at an altitude of 3 km (536 km/hr). Landing speed is 330-350 km/hr (16). The orbital stage should be ready for a new flight within 14 days (160 working hours) after repair. It is designed for use up to 500 times.

Generally speaking, the MTKK is automatically controlled, but the crew may if necessary take over control by using the control levers similar to those which were on the Apollo spacecraft.

The crew of the orbital aircraft, located in a two-level cockpit (volume of 73 m^3) with oxygen-nitrogen microatmosphere, consists of four persons: the

*The cost of the tank is 1.4 million dollars (in 1971 prices) or 15 percent of the total cost of a single voyage of the orbital aircraft (20 percent according to other data).

aircraft commander (first pilot), co-pilot, a specialist responsible for fulfilling the work program and controlling the electric power supply and temperature control and a payload specialist. The co-pilot, besides assisting the commander in controlling the craft, controls the manipulators during orbital operations. The payload specialist carries out scientific work and, unlike other crew members, does not undergo special astronaut training. There are seats for an additional six possible "passengers" (for three according to other data) -- scientists and engineers, who also do not undergo special training (their number may also include women) on the lower deck of the cockpit, generally designed for relaxation of the astronauts. None of them has to tolerate G-loads exceeding 3.

Different cases of emergency situations are provided for.

If one of the sustainer ZhRD or another system fails during the early stage, the flight continues until burnout of the RDTT (their failure is assumed very improbable). The RDTT are then separated and the orbital stage, already flying upside down, turns in the vertical plane by using the available ZhRD and emerges onto the return trajectory; only then is the fuel tank jettisoned and a landing is made (perhaps on a reserve strip).

One revolution around the Earth in a suborbital trajectory is completed if there is a failure at the end of the insertion leg and a landing is made at Vandenberg Air Force Base if the launch originated at Cape Canaveral or at Edwards Air Force Base (California) if the launch originated from Vandenberg Air Force Base.

If the failure is not dangerous, but interferes with performing the intended operations in orbit, a normal low-orbit insertion, descent from it and standard return are carried out.

The orbital stage should complete its first experimental "horizontal" flight in April 1977, being launched at an altitude of 7-8 km from a modified Boeing-747 aircraft; the first experimental "vertical" flight with participation of the booster stage and orbit insertion should be carried out on 1 April 1979. The first operational flight of the MTKK is planned for June 1980.

A total of 5.5 billion dollars has been appropriated for the MTKK development program. The cost of a single copy of the MTKK will be 250 to 350 million dollars according to 1975 prices.

Future Orbital Aircraft

The MTKK project described above is regarded in the United States as a first-generation vehicle whose design corresponds more to the available appropriations than to the real economic requirements and prospects of tomorrow's astronautics. Improvement of the existing version may proceed in two directions: replacement of the booster stage of two RDTT completely by a multi-use winged stage; and replacement of the two RDTT and external tank with a

single winged stage, i.e., return to the two-stage vehicles of the type shown in Figures 7, 8 and 9. We note that the present version of the MTKK is arbitrarily called a "2.5-stage" vehicle; it may be called a three-stage (since acceleration is continued after the second separation of the superfluous mass -- the external tank), but this would be illegal because two stages are included immediately in launch. (The Soviet "Vostok" carrier rocket, for example, was a "2.5-stage" vehicle in this sense.)

An interesting modification of the "Spaceplane" now being developed in the United States was proposed in 1975, which, although it makes it completely multiuse, eliminates or considerably reduces salvage operations of the separated sections, solves the problem of environmental pollution (typical for the use of RDTT), reduces the cost of orbit insertion of 1 kg to 220 dollars (i.e., by 30-40 percent) and avoids the necessity of further paying for development of the booster stage RDTT (development of the orbital stage has essentially been paid for already). RDTT have been completely eliminated in this modification, as a replacement for which a unit of five oxygen-hydrocarbon ZhRD with high pressure in the combustion chambers should be developed; it is placed behind the external tank. The external tank itself has been lengthened to 53.6 m at the expense of the forward section in which an additional tank is located for the hydrocarbon fuel. The launch mass of the system is 1,730 t. Five ZhRD of the described unit and three sustainer ZhRD on the aircraft operate at launch. The first five ZhRD are not separated after burning of the hydrocarbon fuel. The three last ZhRD continue to operate and insert the entire system into a transfer orbit (perigee of 92.5 km and apogee of 370 km), after which the booster impulse at apogee, imparted to the orbital maneuvering ZhRD, inserts a system with mass of 370 kg into a circular orbit at an altitude of 370 km. The payload comprises 27.2 t in this case (launch from Cape Canaveral to the east). After freeing the cargo compartment of the payload, the crew separates the unit of five ZhRD from the external tank and converts it to a cargo compartment for subsequent return to Earth. The external tank remains in orbit or is inserted into the atmosphere by using small RDTT, where it burns up.

It is easy to note that we are concerned here with a single-stage rocket system. Its effectiveness may be increased if the oxygen-carbon ZhRD are separated and brought down on parachutes after use of the unit, which converts the system to a 1.5-stage. This permits orbit insertion of a payload of 40 t and frees the cargo compartment for the additional cargo returned from orbit but, of course, leads to an increase in the cost of the voyage of the orbital aircraft.

The described modification retains the disadvantage inherent to Project Spaceplane -- loss of the external fuel tank. However, the main method of improvement is to develop a totally multiuse single-stage orbital aircraft. Only in this manner, the American specialists feel, can the cost of inserting 1 kg of payload into orbit be reduced to less than 200 dollars.

As in known, the characteristic velocity for launching a satellite into low orbit is approximately equal to 9.5 km/s (orbital velocity is 7.8 km/s plus

gravity and aerodynamic losses of 1.7 km/s). It follows from the well-known Tsiolkovskiy formula that only a very high flow rate of combustion products (high specific engine pulse) makes it possible to achieve this characteristic velocity in the case of a single-stage rocket. One cannot cope without compulsory use of the liquid oxygen-liquid hydrogen combination, which now yields the highest flow rate for chemical engines (on the order of 4.5 km/s) (replacing the oxygen with fluorene, which increases flow rate, would lead to environmental pollution by toxic substances). Improvement of the engines, which can be achieved by increasing the pressure in the combustion chamber, also increases the flow rate.

According to reports of American scientific journals, an important effect is anticipated from using the two-fuel engines now being developed, which use a heavy hydrocarbon fuel (liquid oxygen is the oxidizer) during launch and then transfer to a lightweight fuel -- liquid hydrogen. The first fuel increases launch thrust (due to increasing the second flow rate of fuel) and as a result leads to a decrease of gravity losses (because of faster acceleration).

There is already a number of projects for single-stage orbital aircraft which provide insertion of heavy (more than 60 t), medium (on the order of 18 t) and light (less than 2 t) payloads. Launch from an aircraft is planned in some projects and in-flight refueling is planned in others. Both the payloads and fuel tanks are sometimes placed outside the orbital aircraft body. Horizontal launch using an acceleration trolley is sometimes provided. It is planned to locate the launch pads high above sea level: a payload advantage equal to 7 t is achieved at an altitude of 1,500 m.

Ballistic descent in the atmosphere with vertical braking on the final leg is assumed in many projects. These MTKK are no longer similar to an aircraft, they have no wings, they have a squat shape (large diameter) and resemble a lunar landing vehicle.

Unfortunately, very great engineering difficulties stand in the way of utilizing air-breathing engines (VRD), which consume air as the oxidizer, in orbital aircraft with horizontal launching. They also represent a greater danger to the environment than rocket engines.

Single-stage orbital aircraft will cost must less in operation than 2- and 2.5-stage aircraft, but their development cost is unclear. The fact that modifications of these aircraft will be a means for global cargo shipments is tempting.

Single-stage orbital aircraft, when they become operational, will resemble those "authentic" spacecraft which take off and land at any point on the Earth which enchant us so much in science fiction literature.

UTILIZATION OF ORBITAL AIRCRAFT

Orbit Insertion and Maintenance of Automatic Satellites

The orbital aircraft itself goes into orbit to insert any artificial satellite into a given (not too high) orbit. The crew checks the operating condition of the satellite if necessary. The longitudinal doors of the cargo compartment, which protect the payload against aerodynamic and thermal effects during inserting and during descent in the atmosphere, are then opened. A remote manipulator, which is controlled from the cockpit by the copilot, who observes through a port or by means of a remote camera, extends the satellite into space (a specially installed second manipulator is used if necessary). The MTKK then maneuvers away from the extended satellite.

For orbit insertion and reentry, satellites should have masses and overall dimensions corresponding to the MTKK capabilities. Satellites may be returned to Earth and replaced with new ones as they fail. However, American specialists feel that it is more advantageous to make repairs directly in orbit. If the satellite is located at an altitude where more or less prolonged work may present a danger to the astronauts (an increased radiation zone), it is economically more advantageous to transfer it to a working orbit by using the on-board engine than by towing it with the orbital aircraft itself.

There should usually be modular (block) designs to repair satellites in orbit. This standardization of designs is already being carried out in the United States with regard to a series of satellites to study the Earth's natural resources. It is assumed that a satellite of this series will be serviced an average of five times or a period of 10 years of operation. The MTKK sent into orbit for repair work will carry spare modules in a section of the cargo bay; an additional satellite may be located in the free section of the bay.

The MTKK rendezvous with the satellite to be repaired the same as any other rendezvous in orbit, for example, the rendezvous of the "Soyuz" and "Apollo" spacecraft in the ASTP program. In particular, the launch of the MTKK in this case should occur only when the cosmodrome is in the orbital plane of

the target satellite due to the Earth's rotation. However, the target satellite is more in the position of its orbit at this moment, which make rendezvous impossible. Therefore, the MTKK is initially inserted into a transfer orbit and waits for some time until the mutual position of the satellite and MTKK with respect to the Earth's center becomes favorable for transferring the MTKK into the satellite's orbit. Approach begins after transfer, which, however, is carried out by stopping the MTKK (with respect to the satellite) at a distance of 9 m from it rather than docking. The MTKK then stops its rotation with respect to the satellite by using the attitude control engines (the angular velocities of both bodies should be matched with high accuracy). The remote manipulator then snags the satellite and brings it into contact with the receiving part of the module replacement mechanism. The mechanism removes the old modules from the satellite, fixes them and, by rotating the satellite in different directions, places new modules into it from the magazine, after which the old ones are inserted into the magazine (Figure 14). These operations are carried out automatically under the observation of the crew in the cockpit. The satellite is then undocked, separated from the MTKK by the manipulator and released.

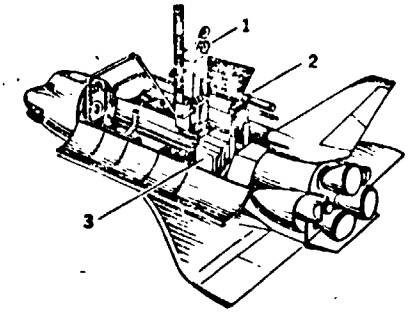

Figure 14. Repair of Satellite for Study of Natural Resources:
1 -- satellite; 2 -- module replacement mechanism;
3 -- rotating magazine

In principle there is no need for the astronaut to emerge into space when performing satellite maintenance operations. The American program does not provide for a space walk unless emergency situations occur, at least during the first 2 years of MTKK operation.

According to calculations of American companies, orbit insertion of meteorological satellites of the "Nimbus" and "Itos" series in an MTKK and repair in orbit will reduce their current operating expenses by 57 percent.

The Orbital Aircraft -- A Space Laboratory

Besides performing its role of a transport vehicle, the orbital aircraft may also be used as an orbital space laboratory if it carries a permanent payload -- special equipment for conducting scientific investigations -- in its

cargo compartment. According to the American Project "Spaceplane," the Spacelab (Spacelab -- space laboratory), now being developed by 17 West European and 3 American companies (the main role among 10 West European countries belongs to West Germany), will be used as such a payload. Expenditures for development of the unit are estimated at 420 million dollars.

The unit will be placed in the aft section of the cargo compartment (due to concepts of rational centering) and its pressurized section will be joined to the cockpit of the orbital stage by a flexible tunnel for transfer of astronauts (life-support system lines will run through this same tunnel). The mass of the unit should not exceed 11.34 t, since the orbital aircraft is capable of returning 14.5 t from orbit, and a reserve is required for taking autonomous satellites on board the aircraft if necessary.

The Spacelab unit will apparently be made in three variants corresponding to different flight programs. The unit in the first variant will consist of only a pressurized section 4.3 m long; in this case the mass of the experimental equipment comprises 5 t. In the second variant (Figure 15), a short open platform will be connected to the pressurized section and the mass of the experimental equipment will comprise 6 t; the length of the unit is 12 m. In the third variant the pressurized section is absent altogether; the entire unit consists of a platform 15 m long, on which will be located equipment with a mass of 9.1 t. The diameter of the unit is 4.3 m in all cases. The platforms may be extended from the cargo compartment without losing contact with the Spacelab unit. The instruments on them may be rotated (the telescopes are equipped with an autonomous attitude control system). The excess heat of the unit is dissipated by means of the radiators of the orbital stage of the MTKK.

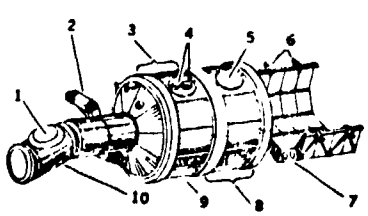

Figure 15. One of the Variants of the Spacelab Module in the Design Stage: 1 -- airlock chamber for space walking; 2 -- connection of service system; 3 -- forward pressurized compartment; 4 -- optical viewing ports; 5 -- lock for experimental investigations; 6 -- mounts; 7 -- open platform for installation of instruments; 8 -- aft pressurized compartment (for experimental instruments); 9 -- insulation; 10 -- tunnel for transfer of crew from cockpit of orbital stage

One model of the Spacelab unit is designed to operate for 5 years and should complete 50 flights lasting up to 30 days. It is serviced by three-seven specialists who are engaged only in scientific work and are completely freed from tasks of controlling the spacecraft (the total number of the laboratory aircraft crew may thus reach 10 persons). The MTKK with the Spacelab module on board will be inserted into circular orbits at altitudes of 200-500 km. The first flight lasting 7 days is planned for April 1980. NASA intends to buy four-six additional flying prototypes of the unit (each costing more than 30 million dollars) and also spare parts from the European Space Agency.

The program of scientific research which is planned by using the Spacelab unit is extremely broad and corresponds in its main features to the usual program of investigations already carried out on Soviet and American orbital stations: astronomy, physics of the Sun and stars, investigations into the field of new materials technology (superpure alloys, semiconductors and so on), communications and navigation technology, geodesy (measuring the distances between points on the Earth's surface with an accuracy up to 1 inch), biology and medicine. Voyages of the MTKK are anticipated which are devoted solely to medical-biological research. If the duration of the experiment exceeds 1 month, special biological satellites (for example with two monkeys on board) will be separated from the MTKK.

High Orbit Operations

Orbital aircraft will be lifted to a relatively low altitude above the Earth's surface. For the MTKK now being developed in the United States, this altitude does not exceed 1,100-1,300 km. A very important, although less numerous part of satellites moving in high orbits is beyond the sphere of maintenance of such vehicles. To overcome this difficulty, it is natural to occupy the greater part of the cargo compartment with rocket apparatus joined to the inserted satellite. This apparatus is called an interorbital transport vehicle (MTA) and also a "space tug."

After orbit insertion of the MTKK, its manipulator extends from the cargo compartment of the MTA. The MTKK moves aside and the MTA begins the independent operation of inserting the satellite into a new orbit.

The ballistic scheme of using the MTA is rather obvious and corresponds completely to orbit insertion of satellites by using single-use carrier rockets.

If the purpose of the operation is to insert the satellite into an elliptical orbit with low perigee and high apogee (similar to orbits of Soviet satellites of the "Molniya-1, -2 and -3" series), then the MTA is launched at point C, selected in orbit 1 so that the axis CD of the calculated orbit 2 occupies the given position after launch of the MTKK at point A and insertion of it into a low orbit 1 at point B. The direction of acceleration coincides with the velocity direction of the MTKK. In this case the MTA achieves a velocity supplementing that of the MTKK to a given value of the initial velocity in orbit 2, point C becomes the perigee and point D becomes the apogee of orbit 2.

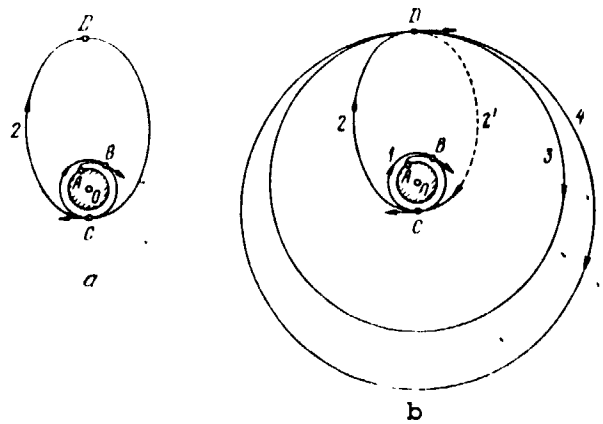

Figure 16. Orbit Insertion by Using MTA: a -- elliptical orbit with high apogee; b -- high circular orbit and elliptical with high apogee. The arrows denote firings of the MTA engines

If the satellite is inserted into a high circular orbit, firing of the engine at apogee D is added to the operations described above, which supplements the apogee velocity to local circular velocity. Thus, satellites in particular will be inserted into a stationary orbit, i.e., into an equatorial orbit for which the rotational period is equal to sidereal days. Actually, if cosmodrome A is not at the equator, the engines must be fired again to transfer the motion of the MTA into this plane at the moment of intersection by a semi-elliptical trajectory of transfer 2 of the Earth's equatorial plane.

If an additional firing at point D forces the MTA velocity to exceed local circular velocity, the satellite is inserted into an elliptical orbit with high perigee (point D).

The MTA releases the satellite at the achieved orbit, moves aside and the insertion operation is completed.

The operation of returning the satellite to Earth (or repair of it) includes the fact that an MTA, not carrying a payload (or carrying replaceable modules), travels an already described path, rendezvous with the satellite, snags it (or leaves in orbit if repair is completed) and returns to the base orbit of the MTTK. Here it "turns over" the satellite to the orbital aircraft, which also returns it to Earth (if repair is not made in the MTTK orbit). The MTA itself remains in the base orbit, being ready for new operations provided that it is refueled.

Return from orbit 3 (Figure 16, b) is provided by a braking impulse equal in value to the acceleration impulse, which was required for orbit insertion 3. The descent to orbit 1 proceeds along a semi-elliptical trajectory 2', symmetrical to trajectory 2 (but the point of return from orbit does not

have to coincide with point D at all). Transfer to orbit 1 is accomplished by a braking burn equal to the acceleration burn for transfer from orbit 1 to orbit 2.

The operation for rendezvous with the satellite may not begin at any moment, but only if the MTA in the required base orbit 1 and the satellite in a high circular orbit 3 (Figure 16, b) are located so that the most advantageous semi-elliptical transfer 2 indicated in Figure 16, b or another (but not just any) transfer permitted by the power resources of the MTA is permissible.

Return from orbit 3 to base orbit 1 should also begin only at a favorable moment which provides rendezvous with the MTTK which is already located in orbit 1. From this viewpoint rendezvous with and maintenance of several satellites by a single vehicle having sufficient power capabilities becomes a difficult task.

It should also be kept in mind that the total characteristic velocities for MTA operations are in no way small. For example, the standard operation of transferring from a low to a stationary orbit and return requires a total characteristic velocity of 8.5 km/s. Therefore, increased exhaust velocities for MTA engines are very desirable. The use of nuclear engines with solid-phase reactor in MTA, which would provide an exhaust velocity of 8-10 km/s, is considered promising. This may not threaten the Earth's surface and atmosphere with contamination, since the MTA may essentially wander permanently in space.

A remarkable feature of the MTA will be the fact that they will accelerate or decelerate at low reactive accelerations (less than g), since they do not have to be launched from Earth and do not have to enter the atmosphere. This not only facilitates the work of the astronauts in the case of a manned MTA, but also essentially simplifies the design of the MTA from the viewpoint of its durability. Individual units of the MTA will be returned to Earth for repair and modification. The operating life of the MTA will be determined more by its moral aging than by losses of durability. Due to the "lightness" of MTA designs, they will essentially have greater launch masses than the MTKK.

It will become very promising in the future to use electrojet engines (electrothermal, electrostatic and magnetohydrodynamic) on the MTA which draw energy from the on-board nuclear reactors or solar cells. This will permit movement of large payloads (due to the high exhaust velocity) from a low to a stationary orbit in a spiral trajectory over a period of several weeks due to the low reactive acceleration (on the order of 10^{-5} to 10^{-4} g). In this case the payload may be very fragile (for example, a large radiotelescope), since there will essentially be no g-forces. These spacecraft will more likely be unmanned cargo craft, since the prolonged stay of man in the radiation belt (where the spacecraft will fly) is not permitted.

Finally, the interorbital transport vehicle may carry out operations which, strictly speaking, do not correspond to its designation. The MTA, having

supplemented the velocity of the orbital aircraft to a value exceeding escape velocity, may carry a payload beyond the sphere of influence of the Earth, transforming it into an artificial probe-planet or sending it toward the planets of the Solar System. The maneuvering range of the MTA reaches the region of the Moon and includes circumlunar orbits (we will discuss this in more detail below).

MTA will also be involved with transferring satellites to new orbits, docking of massive objects, rescue of orbital station crews and satellite inspection.

Designs of Planned Interorbital Transport Vehicles and Their Missions

The first Americal interorbital transport vehicle developed by NASA will become operational no earlier than the end of 1983. This should be an unmanned multimission vehicle, i.e., one capable not only of inserting a satellite into a high orbit, but of also being returned to the base orbit of the MTKK.

The United States Air Force is developing a simplified version of the MTA, based on already existing liquid rockets (Centaur, Agena, Boerner-2 and Transtage), which use carrier rockets as the upper stages, or based on solid-fuel upper stages of Thor-Delta or Scout rockets (Figure 17) for insertion of satellites into high orbits in 1980-1983, when a fleet of space aircraft will already be operating. This will possibly be a single-mission vehicle capable of delivering a satellite with a mass of 5.4 t from a low to a stationary orbit. But it is hoped that a multimission MTA capable of delivering 1.6-2.3 t to a stationary orbit and of returning "empty" to the MTKK orbit on the basis of one of the three modified Centaur, Agena and Transtage rockets (the Centaur is better, but the Agena will be best of all for this).

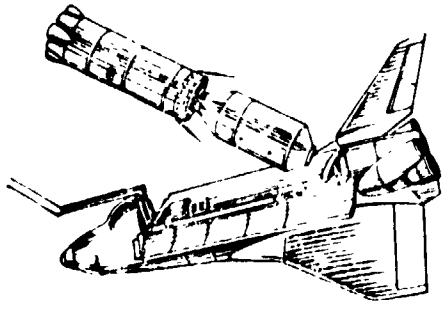

Figure 17. Rocket Stage With Satellite Separates From MTKK Prior to Transfer to High Orbit

The MTA being designed at NASA as an original design will in the worst case deliver 2.3 t to a stationary orbit and return empty. In the improved version it will deliver 2.95 t to a stationary orbit and return empty or will be sent empty into a stationary orbit and deliver a load of 2 t to the base orbit, or will transfer 1.85 t to a stationary orbit and return this same payload. Finally, the future MTA may deliver 3.6 t to a stationary orbit

and return empty or, arriving there empty, delivery 1.8 t to a low orbit or deliver a payload of 2.7 t there and return. According to other data, corresponding values are typical for the next variant: 3.6, 1.6 and 0.9 t, where the mass of the MTA should be 25.7 t, length should be 9 t and diameter should be 4.57 m.

According to certain statements of official NASA representatives, the MTA fleet will consist of five-seven models by 1990. Their total cost will reach 800 million dollars, including development (450 million dollars), operation (250 million dollars, 900,000 dollars per trip) and purchase of finished articles (not less than 100 million dollars).

The possibility of developing a future manned MTA with a crew of four is being considered in the United States (Figure 18). It may stay in a stationary orbit for 7 days. The design will consist of standardized modules. Repair of a stationary satellite may apparently be accomplished best of all by human hands.

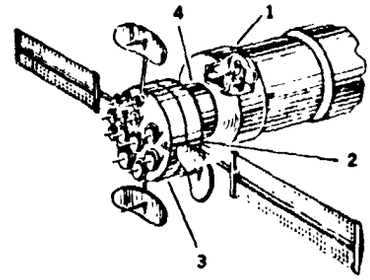

Figure 18. Manned MTA: 1 -- crew compartment; 2 -- standard service systems compartment; 3 -- compartment for installation of specialized equipment; 4 -- adapter

In the American project published in 1974, it is assumed that a multimission manned MTA with a crew of four will consist of a manned section and two rocket stages, delivered to the base orbit separately by two space planes. One stage accelerates the entire system after departure from low orbit, after which it separates immediately and, having rotated in an elliptical orbit, returns to the orbit of the space plane, while the other stage is inserted into a stationary orbit where it remains joined with the manned section and after docking with the satellite, and then returns together with this unit to a low orbit. The modules in the satellite to be repaired will be replaced approximately the same as described above with regard to repair on board the MTKK.

The possibility of developing an orbital refueling complex for MTKK and MTA was reported in the United States. The nucleus of the complex would be a bundle of three units inserted into orbit by three trips of the MTKK, while the fuel would possibly be delivered by a new carrier based on components of the MTKK now being developed, with a payload of 90 t.

Plans for launching automatic interplanetary stations by using MTA are being finalized. They include the launch of a Pioneer station in 1980 into Jupiter orbit and launch of probes from it into the planet's atmosphere; a flight with a perturbation maneuver toward Jupiter in 1989 which brings the station out of the plane of the ecliptic; orbital flights of Pioneer and Mariner spacecraft to Mars prior to 1983; the flight of a station with a solar electrojet propulsion system (SERDU) outside the plane of the ecliptic (1984); a 1985 launch of a Mariner type vehicle with insertion into Jupiter orbit (a more difficult task); rendezvous of the station equipped with SERDU with comet Temple-2 (launch in 1986); and delivery of soil samples from Mars to Earth (launch of an MTA in 1989).

Among new missions whose solution is economically unthinkable without MTKK and MTA should be noted one of essential importance. This is removal of radioactive wastes of the atomic industry from Earth, which will require 200 trips of MTKK annually by the year 2000 according to calculations. The cost of producing electric power by atomic power plants in this case will increase by only 5 percent. It is planned to insert containers with the wastes into the orbits of artificial planets located far from the Earth's orbit or even to send them beyond the Solar System. This new factor inspires optimism under the conditions of the energy crisis and the danger of environmental contamination.

Orbital Repair

There is a specific and ever increasing variety of objects which may not be inserted into near orbit by a single launch of even the most powerful of existing carriers. This may be both due to the fact that the mass of the object exceeds the energy capabilities of the carrier and because the dimensions of the object are too large. The second difficulty may be overcome in some cases (but not in all) (and has been frequently overcome) by using inflatable hardening designs (for example the large spherical satellites Echo-1 and Echo-2) and also developed designs of umbrella or telescopic type (large parabolic antennas of automatic interplanetary stations or extensible 200-meter rod antennas of the Explorer-38 radioastronomy satellite).

However, any orbital complex may essentially be equipped with a means of orbital installation from units delivered from Earth by individual carrier rockets or by a single MTKK making several flights. The economic advantage of MTKK over carrier rockets is obvious in this case. It is also more advantageous to have several launches of standard MTKK than a single launch of a specially developed large carrier rocket capable of inserting the entire object into orbit.

Among the objects being discussed should primarily be included large long-lived orbital stations.

According to an American project, development of which was stopped due to a reduction in appropriations, 17 trips of the MTKK would be used to assemble a long-term orbital station with mass of 110.8 t, designed for 12 persons,

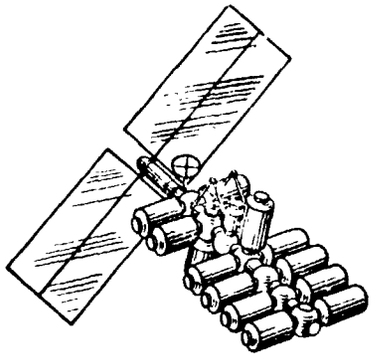

Figure 19. Modular Orbital Station for 12 Persons (United States Project)

from standard modules of two types (mainly 8.8 m long and 4.2 m in diameter) (Figure 19). Six specialists may work in the station in unassembled form after eight launches. Installation is carried out in the following manner: the MTKK initiall docks firmly to the complex already in orbit and only then do the manipulators remove the module delivered from Earth from the cargo compartment and attach it to the complex; the MTKK then undocks and returns to Earth for a new module.

According to statements of American specialists, this project, which was advertised intensively in its time, may still be reborn if it is transformed into an international project: different countries will equip (and possibly produce) standard modules according to their own taste.

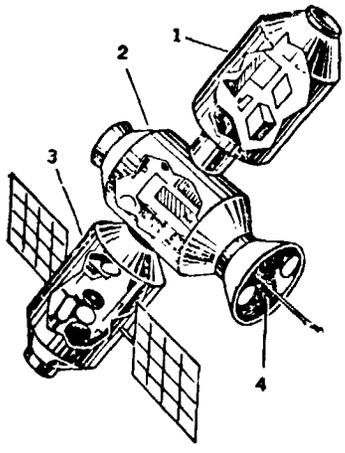

Figure 20. Temporary Modular Orbital Station Assembled by Means of Three Trips of an Orbital Aircraft: 1 -- manned module; 2 -- module for conducting experiments; 3 -- service module; 4 -- docking assembly

A much more modest project of a temporary orbital station assembled from three modules delivered alternately by an MTKK is shown in Figure 20. The only advantage of this station over the spacelab module is the artificial gravity in compartments 1 and 3, created due to rotation of the entire system around the axis of module 2.

Numerous projects of large rotating orbital stations (with artificial gravity), assembled from modules delivered by large single-mission carrier rockets, for example, shortened Saturn-5 carrier rockets (without the third stage) (this rocket inserted the Skylab station into orbit in 1973), were developed comparatively recently. Developments based on the space plane being developed in the United States have now replaced these projects. In 1974 the well-known specialist K. Erike stated that a modular station for 25-100 persons should be developed after 1985. The structures for its own expansion will be produced on this station and new stations will be gemmated from it. According to K. Erike, one should expect construction of the enormous "Astropolis" orbital complex in near space in the future, for which launches of multimission carriers with payloads from 400 to 1,000 t will be required. These "star cities," which are independent technical and economic systems, will also move in the orbits of artificial planets. It is easy to see here development of the famous idea and dream of K. E. Tsiolkovskiy of "ethereal cities."

Among the comparatively more modest projects, which may be regarded as short-term problems, let us point out the proposal for assembly of a gigantic submillimeter radiotelescope (diameter of 90 m, see the figure on the cover) in low orbit. Several flights of MTKK and subsequent towing of the installation to an orbit of 1,300 km by means of an MTA equipped with a solar electrojet propulsion plant would be required for this.

The idea of building a gigantic solar power plant in stationary orbit, advanced in 1968, is truly grandiose, although less fantastic than the "Astropolis" project. This station, now in the preliminary design stage according to American publications of 1975, is designed for 30 years operation with implementation in approximately the year 2000. The use of silicon photoconverters, already tested many times in space, and modern materials in the structure is provided in the project. In order that the output of the solar cells be 5 million kW, their area should be equal to 45 km^2. The mass of the entire structure will comprise 9,570 t. The electric power produced will be converted to microwave energy, directed to some point on Earth by using a stabilized antenna 1 km in diameter. This energy will be received on Earth by using a system of antennas located on a sufficiently large area so that the electromagnetic field intensity does not exceed too much the level which radio and television transmitters emit. The energy is converted to direct high-voltage current for transmission over large distances or into industrial alternating current. It is planned to achieve an output from 2 to 20 million kW, taking losses into account, on Earth (as a function of the area of the solar cells which may not be extremely large: it will be impossible to radiate the excess heat of the generators into space).

It is assumed that the station will be assembled in an orbit of 400 km by using future MTKK with a payload of 180 t or in an orbit of 13,000 km (which is economically more advantageous) with participation of MTA equipped with oxygen-hydrogen ZhRD or nuclear engines (YaRD) with solid-phase reactors (exhaust velocity of 8 km/s) and an available launch mass of 363 t without regard to payload (the payload is equal to 268 t in the case of ZhRD and 468 t when YaRD are used). In both variants the station is moved from the assembly orbit to a stationary orbit by using an MTA with ion engines (based on solar or nuclear power) with an exhaust velocity up to 80 km/s. The possibility of direct assembly in stationary orbit by using the same MTA is not excluded (the payload for ZhRD is now 82 t and that for YaRD is 205 t). Assembly of a prototype station in low orbit is planned for 1990-1992 for digital power transmission. An experimental model of the station may be developed in stationary orbit in 1997.

It is expected that the station will be competitive (in the sense of cost) with regard to thermal, nuclear and hydroelectric power plants. However, damage must also be studied: due to thermal scattering emitted by the ground receiving antennas; due to destruction of the ground cover on the area where the antennas are installed; due to the exhaust gases of the MTKK; and due to effect of the microwave radiation on plants, animals, man, aircraft and communications lines.

There are different opinions on the relationship between the role of automatons and the role of man in orbital operations. Selection itself of the assembly orbit altitude may partially be determined by the role given to man. Man may not spend very much time in elevated radiation zones. The manned flights already carried out clearly demonstrated the advantage the astronaut has in complex situations compared to an ideal automatic device. One may thin think that assembly of complex structures in space requires the direct participation of man. In planning for this, projects are being developed of both individual rocket vehicles ("rocket pack," "rocket chair," and "rocket boots") for astronauts (they have already been tested successfully inside the vast living quarters of the Skylab stations) and also "minitugs" (Figure 21), equipped with manipulators and occupying an intermediate position between the mentioned vehicles and present MTA. These "minitugs" will operate immediately in the region of the space construction project, will move massive articles, will carry out installation and maintenance of the orbital station (for example, they will return autonomous satellites moving together with it in group flight) and so on.

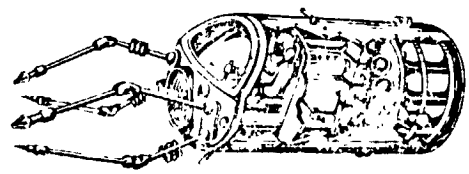

Figure 21. Single-Place "Minitug" With Initial Mass of 3.6 t
(a Project of the Martin Company, 1961)

We can imagine a grandiose and majestic pattern of a future space construction site in its promise in the general features.

Large modules and uncompleted structures are moved smoothly, pushed by the "minitugs." The astronauts with individual rocket apparatus maneuver near the structures. Some distance away is visible the massive body of a mobile atomic power plant, shut off from the construction site by a shield which protects the builders against radiation. Flexible coil-like cables, unsuspended, stretch from the power plant. The flame of the exhaust gases of the interorbital transport vehicle, which has delivered a shift of builders from the dormitory station (its lights are also visible on the sky background) is clearly visible on the background of the black sky. And the blue surface of the Earth floats below. But the Sun is setting. Floodlights flare up brightly: work is also conducted during the 45-minute night which replaces the 45-minute day in low orbit. There is a new flash from the direction of the Earth's surface: an orbital aircraft is arriving.

Maintenance of Orbital Stations

Regular replacement of the crews of long-term orbital stations is a classical problem of orbital aircraft. Even when it was assumed that an orbital station would be assembled by using modules delivered by single mission carrier rockets (and even from their empty last stages), even then the honor of replacing the crews was given to rocket planes. This will be the simplest duty of space planes if the station is moving in a low orbit. Of course interorbital transport vehicles come into action in case of a high orbit. But at a sufficiently high level of becoming accustomed to near space when the flight itineraries to the station and other orbits acquire the nature of permanent lines of communication, all operations must be organized more purposefully from the economic viewpoint.

According to K. Erike, who does not doubt that long-term stations will occur and will be developed in stationary orbit, a permanent auxiliary station in an intermediate elliptical orbit, located between the low and stationary orbits, must be created. Transfer to this intermediate station from low orbit (and vice versa) would be accomplished by using a simplified "perigee" MTA and from it to a stationary orbit (and vice versa) by using another "apogee" MTA. These vehicles would be at one or another of the three orbits at various times. Economy is achieved due to simplifying the vehicle designs (different requirements on the engines at perigee and apogee, freeing of navigational equipment required only in intermediate orbit and of life support elements and so on). According to K. Erike, it would be more economically advantageous (with regard to the number of trips) to use a system with oxygen-hydrogen ZhRD instead of an MTA with YaRD. Instead of using an apogee MTA, it would be even more advantageous to equip the station in intermediate orbit with an electrojet propulsion plant.

It should be noted that the motion of an MTA in such an elongated orbit as the indicated intermediate type should undergo considerable lunar-solar

perturbations, which may raise the orbit perigee, or which is worse, lower it into the atmosphere and alter the apogee. The crew of the MTA should follow this closely and correct the orbit.

The Operating Model of the American Space Transport System

According to data for May 1975, specialists of the Department of Future Mission Planning and Payloads in the central apparatus of NASA have developed a new operating model of the MTKK. According to it, MTKK should complete 572 flights from 1980 through 1991. The number of payloads will be much greater, since several satellites will frequently be inserted during a single flight. The greater the total mass of the payload inserted during a single flight, the more economical the flight is. Specific payloads are already being planned for the first 20 flights (disregarding the 6 experimental flights, including 3 in 1979). During the transition period of 1980-1983 single mission carrier rockets will be the reserve for carrying out certain complex flights and for emergency situations of the MTKK. By 1983 a fleet of five models of the orbital stage should become operational. A total of 226 flights with the Spacelab module and 197 flights in combination with the first- and second-generation MTA will be completed (the maximum number of flights with the MTA will be 22 in 1985). Five flights, including three with a payload in combination with an MTA and two with the Spacelab module, will be completed in 1980. In 1981 15 flights will be completed (including 8 with an MTA and 6 with the Spacelab module); 24 flights will be completed in 1982 (12 with MTA and 12 with the Spacelab module); and 48 flights will be performed in 1983 (15 with the MTA and 17 with the Spacelab module). A total of 60 flights each of the MTKK annually will be made from 1984 through 1991. The number of flights with the Spacelab module will increase annually from 19 in 1984 to 24 in 1991. The average will be 20 flights each with the MTA annually.

The given model will be used in economic calculations.

The inflation of the past few years has a strong effect on the rates of development of the space plane. The flight plans for the 1980's are being cut back (in 1974 725 flights were still figured in the operating model of MTKK).

THE LUNAR TRANSPORT SYSTEM

Theoretical Variants of Lunar Expeditions

The extremely high cost of lunar expeditions, as is known, led to reduction of the initially planned number of flights in the Apollo Program. The American plans for space flights do not provide a flight of man to the Moon for at least 15 years. Development of a permanent scientific station on the Moon with the crew replaced periodically, which is apparently much more feasible than sensational short landings, may not in itself be imaginable under conditions when a ticket to the Moon costs hundreds of millions of dollars!

To analyze the possibilities of reducing the cost of a lunar expedition, let us consider theoretically the possible variants of human flight to our natural satellite.

Three such main variants are known from the literature.

The first variant -- a direct expedition. A multistage rocket inserts a spacecraft into a lunar flight trajectory, which itself includes several rocket stages. The spacecraft is usually first inserted into a near-earth parking orbit, from which it is launched toward the Moon at the required moment (whether by using the last stage of the carrier rocket or its own propulsion plant is immaterial; everything depends on where one considers the end of the carrier rocket and the beginning of the spacecraft). This maneuver is mainly required because it permits reduction of gravity losses to a minimum due to a slanting boost, when no flight would occur during the sidereal month. The initial velocity of the passive flight toward the Moon is equal to approximately 11 km/s (the characteristic velocity is approximately 13 km/s).

The flight trajectory may be selected so that it brings the spacecraft to a direct landing on the Moon and the rate of fall (somewhat more than 2.5 km/s) should then be attenuated by a retrorocket. In this case intermediate insertion into a low circumlunar orbit is also possible, which does not yield an energy advantage, but is convenient in many respects (the possibility of landing at a point of the surface unsuitable for direct landing, an

emergency launch to Earth, refining the landing site and if the site is suitable and so on). The jettisoned stage (for example, in the form of empty fuel tanks), which will not be used any more, may be left on the Moon with descent from a circumlunar orbit.

Return from the Moon may (but generally speaking does not have to) be accompanied by leaving the stage on it that burned out during landing (moreover it also plays the role of a "launch pad") and insertion into a parking circumlunar orbit (if direct flight to Earth is otherwise impossible). The velocity reaches 2.5-3 km/s with launch from this orbit. The recovery capsule, which also makes gliding descent, enters the Earth's atmosphere on a slant at a geocentric velocity of 11 km/s, while the remaining part of the spacecraft burns up upon reentry. Preliminary insertion into near-earth orbit by retrorocket firing does not make sense, since this would increase the mass of the spacecraft many times and the launch mass of the carrier rocket as well.

The second variant -- assembly of the spacecraft in near-earth orbit. In this case the already mentioned low parking orbit is used as an assembly orbit. The sence of this assembly was seen in time in the fact that two or three small rockets could be constructed at a given level of development of technology, whereas one large rocket with a payload double or triple the total payload of small rockets could not be constructed. And what if it could be constructed? In this case the method does not yield an energy advantage and it also does not yield an advantage in mass characteristics (the total launch mass of two or three small rockets is approximately equal to the launch mass of a large one). With regard to the economic aspect, the method, on the contrary, does yield an advantage since the cost of the rocket is in no way proportional to its mass: for example, a large rocket has a single expensive control system, while three small ones have three systems just as expensive. So that construction of large rockets, from the viewpoint of the cost per kilogram of payload, is generally much more advantageous than construction of small ones and the practice of space rocket building confirms this.*

Everything occurs the same as in the first variant with regard to the last flight stages to the Moon and return.

The third variant -- separation and approach in near-earth orbit. Insertion into a circumlunar orbit is now obligatory. In this case only part of the spacecraft -- the lunar landing vehicle -- separates from the mother ship and lands, while something in no way discardable remains in orbit (the unspent stage) and the equipment required for the return trip when the lunar vehicle is launched from the surface of the night side (leaving its landing

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*For details see the booklet of the series "Cosmonautics and Astronomy": A. D. Koval' and A. A. Tishchenko, "Kosmicheskiye issledovaniya i ekonomika" [Space Research and Economics], Moscow, Znaniye, 1973.

stage there) in order to join the main part of the spacecraft in orbit. After the astronauts have transferred to the main spacecraft, the takeoff stage of the lunar vehicle remains in orbit while the spacecraft itself flies to Earth. Further operations on return to Earth do not differ from the first two variants of a lunar expedition.

The described scheme of the expedition was, as is known, first proposed by Yu. V. Kondratyuk and one similar to it was used in the American Apollo Program. Although the Saturn-5 carrier rocket was also a gigantic structure in this program (111 m long together with the command module and the launch mass was approximately 3,000 t), it was even so considerably smaller than the rockets designed up until that time by the first variant.

The advantages of the third variant are that a considerably smaller mass lands on and takes off from the Moon than in the first two variants. This saves energy consumption (and especially fuel) and this means (although not in direct proportion) that the cost of the entire expedition is reduced.

The Lunar Transport Spacecraft

It is easy to see something favorable to recovery and repeated use of parts of the lunar space complex. In fact, many parts of the spacecraft, although they are not returned to the Earth's surface, also are not lost completely, since they are retained intact in lunar orbits and on the lunar surface. The stages which insert sections of the spacecraft into a near-earth assembly orbit in the second variant, remain in this orbit and, consequently, are also undamaged until they enter the dense layers of the atmosphere. These stages may remain in near-earth orbit in the first and third variants, but launches from this orbit may not be made, as was done in the Apollo program.

The lower stages of the carrier rockets falling to the Earth in all three variants may essentially be recovered, although this is a very difficult task. Joining wings to the first stage of the Saturn-5 lunar rocket would have increased its mass by 10 percent according to American calculations. In an American paper of 1967, it was proposed to cope without wings, but to redesign the rocket tanks in a special manner: in assembled form the rocket stage has the usual cylindrical shape, the tanks are rearranged into a new configuration without each losing its rigidity after burnup of the fuel and they now have a lift force, which makes a horizontal landing on a runway possible.

But the difficulties of recovering large stages typical for the first and third variants of lunar expeditions do not exist for the second variant, since assembly may be accomplished by using small rockets and even better by using orbital aircraft. Whereas a mass on the order of 100 t (the Apollo program) is in a near-earth parking orbit according to the third variant, approximately four flights of an MTKK of the Spaceplane class being designed in the United States are sufficient to assemble the corresponding spacecraft.

There is still the unrecovered part of the spacecraft which burns up upon return after reentry into the Earth's atmosphere. Two solutions may be proposed here. First, transfer of the entire spacecraft (with propulsion plant) into a low near-earth orbit by firing the retrorockets: the braking pulse of 3 km/s reduces the velocity to orbital velocity. We actually know that this should lead to very high additional energy expenditures and, consequently, to an increase in the cost of a single expedition, but if the part of the spacecraft recoverable in orbit is used repeatedly, this changes the pattern significantly. Second, the method of insertion into low near-earth orbit -- aerodynamic braking or, as is frequently said, using the Earth's atmosphere as a braking cushion, is theoretically possible and almost gratis from the energy viewpoint. In particular the variant of skipping in the atmosphere is feasible in this case. We recall that when the retrorockets of the recovery capsules of the Soviet stations of the "Zond" series were fired in the Earth's atmosphere, their velocity during the first descent was reduced from 11 to 7.6 km/s, after which they ricocheted from the atmosphere (before the second and final entry into it). A small acceleration firing at the upper point of the exit trajectory from the atmosphere could essentially reduce the velocity of the capsule to orbital. This method of orbit insertion around a planet was investigated in a large number of Soviet and foreign investigations and many specific results were published with respect to launches of satellites to Mars, Venus and Jupiter.

By arriving at logical conclusions from the foregoing, we can now note in general outlines the scheme of a lunar transport system. A lunar cargo or passenger spacecraft is assembled in near-earth orbit from modules delivered by orbital aircraft and is essentially an MTA which travels between near-earth and circumlunar orbits. It is called the lunar transport spacecraft (LTK) in American papers. Trips between circumlunar orbit and the lunar surface may be carried out by special landing vehicles according to the third variant of the lunar expedition (they are called lunar space tugs in these papers).

But if the LTK is equipped with landing legs, they would themselves be able to land intact on the Moon (similar to the first and second variants). The simplicity of modifying the vehicle for landing is explained by the absence of an atmosphere near the Moon.

Low-Thrust Lunar Cargo Spacecraft

Motion in numerous revolutions of a near-earth spiral, a considerable part of which will lie within the radiation belt, will make it difficult for a long time for man to remain on board an electric LTK. Therefore, a low-thrust LTK will be used more for large cargo shipments from the orbit of an Earth satellite to the orbit of a lunar satellite. The support structure of such an LTK may have a small mass, since one essentially need not be concerned about its strength under the conditions of the negligible g-forces caused by the low thrust. In some designs of electric spacecraft, individual modules (living, propulsion and power) are even joined to each other by cables

which tighten only slightly due to the low acceleration, rather than a rigid structure.

A spiral trajectory of the active motion of an electric cargo spacecraft is transformed during the last revolution into a passive elliptical trajectory which enters the lunar sphere of influence. The velocity of the LTK with respect to the Moon will be too high inside its sphere of activity so that the lunar gravity is able to capture the spacecraft independently. Additional braking by means of low-thrust engines is required. It should begin in the lunar sphere of activity or even at the half-way point to the Moon. Braking inside the lunar sphere of activity inserts the spacecraft into a low orbit of the lunar satellite. Hence the payload will be delivered to the surface by lunar tugs.

In a 1963 paper, it was proposed to insert the cargo spacecraft, equipped with a nuclear power plant and ion engine, into a near-earth orbit 480 km in altitude by using a Saturn-5 type rocket or one even larger. Instead of this, one could of course use several trips of an MTKK. In one of the calculated variants, the entire flight continues for approximately 63 days. The payload delivered to circumlunar orbit comprises 20-30 percent of the total mass of the spacecraft at the moment of launch from the orbit of the Earth satellite (this also includes the propulsion system for a soft landing on the Moon, which makes up 56 percent of the payload).

One can imagine regular trips of large multimission electric cargo LTK in the future, controlled automatically and which supply permanent lunar bases with everything necessary through a circumlunar spaceport. These trips will occur together with "express" flights of passenger LTK.

A Circumlunar Orbital Spaceport-Station

Normal functioning of the lunar transport system described assumes development of permanently operating spaceports near the Earth and Moon, i.e., orbital stations containing fuel reserves and which provide maintenance of the LTK. A circumlunar spaceport, like one near Earth, may also be used "according to compatibility" as an observatory for lunar research. In this case it should be located near the Moon.

Let us consider in more detail the operation of a circumlunar spaceport.

An LTK arriving from near-earth orbit, besides cargo and passengers, delivers fuel to the spaceport for the lunar tugs based on it. The tugs deliver cargo and astronauts to the lunar surface, while the LTK gathers cargo (scientific materials, minerals and so on) and personnel returning to the Earth and leaves on the return trip. At the same time the spaceport should be a communications and control center for all lunar operations and orbits around it: rendezvous and docking of transport spacecraft, landings and takeoffs of unmanned lunar tugs and movements of lunar roving vehicles. It provides communications with the expeditions on the lunar surface. The spaceport personnel should control the manipulators on the orbital vehicles

which service automatic lunar satellites. The spaceport will be used as a hangar and repair station for these vehicles and possibly for the lunar roving vehicles as well. It will also be a base for rescue operations in circumlunar orbits.

At what altitude and in what plane should the orbit of the spaceport be located?

Based mainly on the convenience of scientific investigations, the future planning group of the United States President in 1969 proposed that a spaceport be created in a polar circumlunar orbit 110 km in altitude (within the framework of an extensive lunar research program designed for the 1980's, which was also not confirmed). However, in the opinion of the authors of a number of papers published at the end of the 1960's, other more suitable orbits may also be selected for a station playing the role of a lunar spaceport. They proposed that the spaceports be located at the so-called collinear libration points L_1 and L_2.

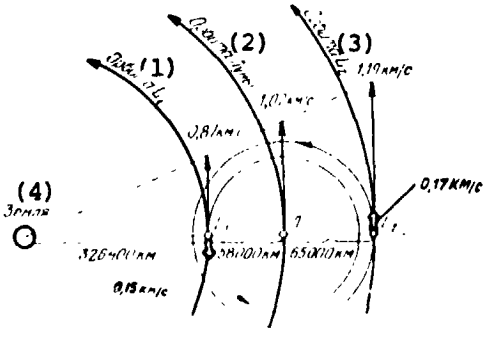

Figure 22. Libration Satellites L_1 and L_2. The geocentric orbits and geocentric velocities are shown by the more solid lines; selenocentric velocities are shown by the wide and short arrows. Scale is not observed

KEY:

1. Orbit L_1
2. Lunar orbit
3. Orbit L_2
4. Earth

In solving the three-body problem (the Earth, Moon and the spacecraft) in its idealized postulation (the Moon is assumed to be moving around the Earth in a circular orbit with radius of 384,000 km rather than in a slightly elliptical orbit, as in reality) follows in particular the following result. If a spacecraft is delivered to point L_1, located on the Earth-Moon line at a distance of 326,400 km from the center of the Earth and 58,000 km from the center of the Moon and if it is given a direction perpendicular to the Earth-Moon line (Figure 22) and a velocity of 0.87 km/s with respect to the Earth (more accurately, "in the geocentric system of axes"), the motion of the vehicle will further occur around the Earth in a circular orbit with

radius of 326,400 km with the same rotational period as the Moon. The latter statement indicates that the detected motion sharply contradicts the usual "laws of motion" of satellites, which did not take into account the effect of "third bodies" (the Moon in the given case).

A similar situation exists at point L_2 as well, but now located at a distance of 65,000 km behind the center of the Moon: the spacecraft moves around the Earth in a circular orbit with radius of 449,400 km at a velocity of 1.19 km/s with respect to Earth.

It is curious that bodies at point L_1 and L_2 are not only Earth satellites, but lunar satellites as well and therefore have circular orbits with respect to the Moon ("in the selenocentric reference"). One may ascertain this by mentally moving the Moon in its orbit in Figure 22 and noting the positions which bodies L_1 and L_2, remaining on the Earth-Moon line, will occupy in this case: they will no longer be to the left and right of the Moon, but above and below it within one-quarter revolution, they will be to the right and to the left within another quarter revolution and so on. Their rotational periods -- 27 days each -- are considerably greater than they should have been if only lunar gravity were acting on them.

We shall call satellites at points L_1 and L_2 libration satellites, although we cannot determine exactly whose satellites they are -- Earth or lunar. The motions of libration satellites are completely incorrect if some single gravitational field -- that of the earth or Moon -- is considered. If the attraction of the Earth and Moon are taken into account simultaneously, their motions are completely regular.

Unfortunately, these motions are unstable: large perturbations move the satellites from point L_1 and L_2. Moreover, there are always gravitational perturbations from the direction of the Sun and the actual orbit of the Moon is not circular. However, the spaceports may be held within the vicinity of the libration points by using electrojet engines or even a solar sail, which create thrust to compensate for the slight perturbations.* (Incidentally, a low polar circumlunar orbit also requires constant concern about compensating for the perturbations whose sources are "mascons" -- concentrations of excess mass at individual points of the Moon).

It is interesting to note that since the Moon is turned with one side toward the Earth as if rigidly seated on the Earth-Moon axis, libration satellites for the Moon are stationary. Spaceports at points L_1 and L_2 are an additional advantage.

Insertion of a libration satellite to point L_1 should be carried out as follows: the satellite is inserted to point L_1 along a trajectory close to

*Besides libration points L_1 and L_2, the three-body problem also contains three additional libration points but, since they do not play any role in circumlunar spaceports, we will not consider them.

semi-elliptical (because of lunar perturbations it deviates from an elliptical shape near the apogee L_1), where a pulse of approximately 0.65 km/s is imparted to it, which brings its velocity up to 0.87 km/s with respect to the Earth (0.15 km/s with respect to the Moon).

An insertion trajectory to point L_2 is much more complicated, since the spacecraft, passing deep within the lunar sphere of influence, experiences the very strong effect of lunar gravity. Firing the on-board engine at a point near the Moon holds the spacecraft inside the lunar sphere of gravity and transfers it to a trajectory passing through point L_2. Yet another firing transfers it into a circular circumlunar orbit with radius of 65,000 km or, which is the same thing, it remains on the rotating Earth-Moon line or it is transferred to a circumlunar orbit with radius of 449,400 km. (We used different expressions to indicate the same phenomenon by using different coordinate systems: 1) selenocentric, 2) that bound to the Earth-Moon line and 3) geocentric.)

Spacecraft parked at points L_1 and L_2 are returned along trajectories similar to those described, but in the opposite direction.

LTK, which reach the libration points (and, which, incidentally, also insert them into a low circumlunar orbit), will probably be two-stage (if they are not nuclear), while the first stage, having returned automatically along an elliptical orbit to the launch point, is transferred by a retarding pulse to the orbit of the near-earth spaceport. The lunar tugs flying to the Moon from the libration points will also be two-stage; the first stages will insert them into a low-circumlunar parking orbit and will then return them from it to the spaceport.

The lunar tugs based at the libration points require a greater amount of fuel than tugs servicing the spaceport in low orbit, since the former approach the Moon at a velocity close to parabolic (2.4 km/s) and to transfer to low orbit they require a retarding pulse of approximately 0.7 km/s (this value is also the excess characteristic velocity upon descent to the Moon from the libration point compared to descent from a low orbit). But all the points of the lunar surface (including the side of the Moon invisible from the spaceport) are essentially accessible from the libration spaceport, since very low expenditures of velocity are required to rotate the plane of a selenocentric orbit by any angle due to the small value of the selenocentric velocities of libration stations (0.15 km/s at point L_1 and 0.17 km/s at point L_2). We note that the trajectory of a lunar tug descending from a libration point may not be regarded as elliptical due to the strong perturbations on the part of the Earth on the leg remote from the Moon. The descent will continue for approximately 24 hours.

But the main advantage of libration spaceports is in the role that they play as communications and control centers for all operations near and on the Moon. True, it is much more advantageous to insert a "translunar" space point to the vicinity of point L_2 rather than to the point itself so that it moves in a closed orbit around point L_2 (a "halo-orbit," Figure 23)

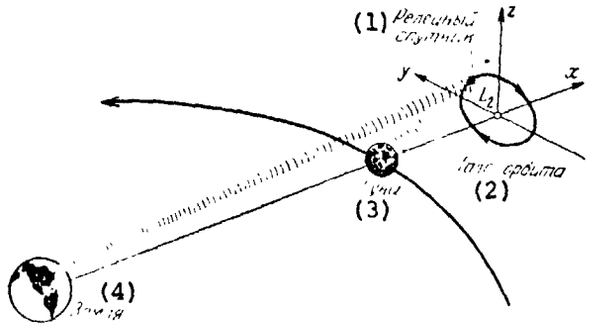

Figure 23. Radio Relay Station in Halo-Orbit Around Point L_2

KEY:

1. Relay satellite
2. Halo-orbit
3. Moon
4. Earth

and of course, together with point L_2 -- around the Earth, according to one of the solutions of the three-body problem. A station in a radius of a halo-orbit of 3,500 km will complete a revolution within 2 weeks. Unlike a satellite at point L_2, a satellite in a halo-orbit will always be visible from Earth (and the Moon will be visible inside its halo-orbit). It may provide Earth communications with any point of the unseen lunar hemisphere, while Earth may provide communications of the spaceport in halo-orbit with any point of the visible hemisphere. If the Earth is replaced in this scheme by a relay satellite at point L_1 (from which the halo-orbit is also visible), we achieve a global communications system independent of Earth. This reduces the transit time of radio signals, which may be important, for example, in controlling manipulators and lunar roving vehicles, invisible from the spaceport in halo-orbit.

Control of halo-orbit perturbations requires annual expenditures of characteristic velocity on the order of 150 m/s. If the station is rarely permitted to set behind the Moon, 30 m/s annually will also be adequate.

A spaceport in low polar orbit (at an altitude of approximately 110 km) does not compete with one in halo-orbit at a communications and control center: it does not set behind the Moon no more than 3 days per month; the lunar base will have no contact with the orbital station for 11 days (the Moon rotates inside the satellite's orbit too slowly); when these contacts do occur, each of them will continue for approximately 10 minutes only per revolution (the flight time of a satellite through the lunar sky). Such a spaceport cannot cope without an intact system of lunar relay satellites.

AN INTERPLANETARY TRANSPORT SYSTEM

Orbital Assembly of an Interplanetary Spacecraft

The complexity and long duration of expeditions to the planets of the Solar System lead the payload of an interplanetary spacecraft to large theoretical values. This value is assumed equal to 50-100 t in most investigations in preliminary (very sketchy) design of interplanetary expeditions.

To estimate the initial mass of a multistage spacecraft launched from a low near-earth orbit, the following formula may be used

$$P = e^{V/w}\left[\frac{s-1}{s-e^{V/(nw)}}\right]^n$$

for a so-called relative initial mass of $P = M_0/m$, where M_0 is the initial mass of the interplanetary spacecraft; m is the payload mass; V is the total characteristic velocity; w is the exhaust velocity,* assumed identical for all stages; n is the number of stages; and s is the design characteristic of the stage (the ratio of the total mass of the stage to its mass after burnout of the fuel), also identical for all stages. Each stage imparts a velocity of V/n with the assumptions made.

Let us estimate M_0 for an expedition to Mars at adequately optimistic assumptions. Let the flights to Mars and return take place along trajectories which require a minimum launch velocity from a near-earth orbit (an altitude of 200 km) and from the surface of Mars; the landing on Mars, like a landing on Earth, does not require jet braking (here we do not have complete confidence with regard to a landing on Mars, since the mass of the spacecraft is large and the atmosphere is very rarefied). If the orbital inclination of Mars to the plane of the ecliptic is disregarded in this case, the total characteristic velocity with regard to the gravity losses comprises V = 10 km/s

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*The exhaust velocity w(m/s) is equal to $P_{ud}g(s)$, where P_{ud} is the specific thrust (specific impulse) (s) and g - 9.8 m/s^2 is the acceleration of gravity.

(launch velocity from orbit of 3.6 km/s plus the takeoff velocity from Mars of 5.7 km/s plus the gravity losses of 0.7 km/s). If it is assumed that s = 15, w = 5 km/s (fluorene-hydrogen fuel under high pressure) and n = 3, then P = 9.118. At m = 50 t the initial mass is M_0 = 456 t. (In the case of n = = 2 it will be almost the same thing: P = 9.601 and M_0 = 480 t, but in this case the half-empty first stage should have descended to Mars.) In order to assemble such a spacecraft in orbit, five launches of such rockets as the Saturn-5 or approximately 18 flights of orbital aircraft of the Spaceplane type would be required. However, at w = 10 km/s (a solid-phase nuclear engine), a single-stage spacecraft (n = 1) would have a mass of 155 t (P = = 3.099); it would be sufficient to launch a single modified Saturn-5 rocket, or six flights of an orbital aircraft of the Spaceplane type, or a single flight of a single-stage multimission "Astroplane" vehicle, mentioned on pages 10 and 11, to insert it into orbit.

The projects developed in detail and published in the scientific literature usually provide a flight to Mars or return along a "nonminimal" trajectory which intersects the orbit of the planet (rather than being tangent to it), which reduces the length of the expedition from 1,000 to 400-500 days, but increases the total characteristic velocity by 3-4 km/s and the initial mass of the spacecraft in orbit to 700-1,000 t (for different epochs when expeditions are taking place; the fuel is oxygen-hydrogen).* Thus, the number of trips of an MTKK of the Spaceplane type increases to 40. Consequently, organization of an expedition to Mars without using nuclear engines is a considerably more difficult enterprise than construction of a large orbital station.

An expedition to the surface of Mercury is even more difficult: V = 30 km/s; at w = 10 km/s (a nuclear engine!), s = 20 and n = 2, then P $\simeq$ 30.11 and $M_0 \simeq$ 1,500 t (at m = 50 t). For operations which require such high energy expenditures it is obviously desirable to use orbital aircraft with payloads on the order of that for which the "Astroplane" (pages 10 and 11) was designed at the beginning of development of the MTKK.

An Interorbital Transport Vehicle Services the Return of the Interplanetary Expedition

We have just considered assembly of an interplanetary spacecraft preceding its launch from a near-earth orbit. Let us now turn to operations which may accompany its return.

Upon return from an interplanetary expedition, the spacecraft may enter a near-earth orbit -- parking orbit. If this orbit is low, the spacecraft crew is brought to Earth on board the MTKK. If the parking orbit is high, an MTA first delivers the crew (or even the entire spacecraft) to a low orbit, from which the crew returns to Earth on board the MTKK.

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*For details see the book: V. I. Levantovskiy, "Mekhanika kosmicheskogo poleta v elementarnom izlozhenii" [The Mechanics of Space Flight in Elementary Exposition], Second Edition, Moscow, Nauka, 1974.

Transfer to a high parking orbit may be feasible if it is dictated by the necessity of minizing the total characteristic velocity. Upon return from Mars along a Hohman trajectory (i.e., along a trajectory requiring minimum energy expenditures), this optimum altitude of the circular orbit will be 85,500 km. The altitude will comprise 122,000 km upon return from Venus. Upon return from Uranus, Neptune or Pluto along Hohman trajectories, the optimum circular parking orbit will be lower. These orbits are inside the radiation belt upon returns from Jupiter, Saturn and Mercury.

Finally, an elliptical parking orbit is also possible from which the crew will be delivered by the MTA to a low circular orbit. If the perigee of the elliptical orbit is located in the low circular orbit, the MTA, located in the circular orbit, initially accelerates to equalize its velocity with that of the interplanetary spacecraft at perigee and then, making a single revolution together with it in the parking orbit, fires its retrorockets at perigee and awaits the arrival of the MTKK. This maneuver was provided in the project published in 1972 (the journal Astronautics and Aeronautics) of an expedition to a low orbit around Jupiter and to its satellites Io, Europa, Ganymede and Callisto, whereas an intermediate fuel base is created in an orbit around Callisto, on which is concentrated the hydrogen extracted in the atmosphere of Jupiter. This project, which is almost imaginary, is based, however, on the use of a YaRD with a specific pulse of 825 s. The spacecraft and crew of six is returned to a near-earth parking orbit with a perigee at an altitude of 160 km and apogee at an altitude of 19,000 km.

Regardless of what the parking orbit would be to which the interplanetary spacecraft is returned,* it makes sense only if a second multiuse of the spacecraft is assumed. In the opposite case it is sufficient to recover the capsule and crew, which has reentered the atmosphere in gliding flight. Reentry into the atmosphere may occur at very high hyperbolic velocities. For example, even upon return from Mars the reentry velocity may exceed 20 km/s.

If difficulties arise in bringing the crew to Earth in such a case and if in addition the returned spacecraft has no fuel at all for maneuvering, an MTA located until then in an elliptical orbit may rendezvous with it on a fly-past hyperbolic trajectory. After rendezvous and taking the astronauts on board, the MTA fires its retrorockets immediately in order to go into a new elliptical orbit (hardly differing from the old one), where another MTA then rendezvous with it. If the first MTA is equipped with nuclear engines, it may also go into a low circular orbit independently to await the MTKK, since it will have a sufficient energy reserve for extensive maneuvering.

Multimission Interplanetary Transport Spacecraft

Return of an interplanetary spacecraft to a near-earth orbit makes it a multimission only if the stages separated from it on the long trip to the

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*Generally speaking, it may also be achieved by aerodynamic braking (see page 47).

planet of destination and return are not lost, but were recovered for repeated utilization or if these stages did not exist at all, i.e., the spacecraft was a single-stage.

For example, let us consider the purely academic example presented above of an expedition to Mars with a total characteristic velocity of V = 10 km/s (page 56). Each of the three stages should have given the spacecraft a velocity of 3.33 km/s and upon launch from Earth orbit a slight amount of fuel of the second stage should have been used; the second stage would be unable to achieve circular velocity (equal to 3.5 km/s) upon launch from Mars and would crash onto Mars, while the third stage would insert the spacecraft into a low parking orbit and from there onto a flight trajectory toward Earth. Thus, the first stage would go into the orbit of an artificial planet without reaching the orbit of Mars, the second would remain on Mars and the third would either burn up upon reentry into the Earth's atmosphere or would be inserted into an orbit by aerodynamic braking (we did not provide fuel for jet braking). At least the first two stages would be lost forever.

However, if the spacecraft is equipped with nuclear engines, with an exhaust velocity, let us say, of w = 10 km/s, we may consider even jet insertion of the spacecraft into near-earth orbit (a braking pulse of 3.6 km/s) and leave it a single-stage in this case, as on page 56. In fact, even an increase of the total characteristic velocity to 15 km/s (more than 1 km/s of the reserve velocity) yields P = 5.965 upon the previous assumptions, i.e., M_0 = = 298 t. This is 1.5 times less than the mass of a three-stage spacecraft with ZhRD operating on fluorene and hydrogen, incapable of even going into near-earth orbit by rocket firing!

It is obvious from this example how important it is to improve rocket propulsion systems, which leads to a sharp increase of exhaust velocity (specific impulse). It is expected that in time (sometimes indicated within several decades and sometimes by the end of the 20th century) so-called gas-phase nuclear engines will be developed which provide an exhaust velocity up to 70 km/s. That which now seems fiction will then become possible. For example, at V = 30 km/s a 150-ton single-stage spacecraft will deliver an expedition to Mars and return to Earth within 153 days and which will spend 13 days on Mars (the total characteristic velocity is 30 km/s; the landing on Mars is completely aerodynamic). At w = 60 km/s the spacecraft for this same operation would have a mass of 85 t and it would be capable of completing an expedition to the surface of Mercury, whereas a three-stage spacecraft with fluorene-hydrogen ZhRD to Mercury would have to have a mass of 50,000 t in orbit, while a five-stage spacecraft would be approximately half as much. It is curious that the spacecraft to Mercury would have an enormous mass -- 1,500 t* -- even with solid-phase YaRD (w = 10 km/s).

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*A payload of m = 50 t and s = 15 was previously assumed everywhere. The results of the calculations are borrowed from tables presented in the book cited on page 56.

Development of the solid-phase "Nerva" YaRD in the United States was stopped at the test-stand stage due to reduction of budget appropriations.

Interplanetary spacecraft equipped with electrojet engines (ERD) will also clearly be multimission. These spacecraft will have high relative payloads (due to the high exhaust velocities), but very low thrusts and correspondingly low reactive accelerations (on the order of 10^{-5} to 10^{-4} g). This will force them to move for a long time in an initial spiral leg of Earth departure and a final spiral leg of descent into orbit around the planet of destination during the flight "there," and also on similar legs during the return flight. They will not transport expeditions but rather will provide cargo shipments from a near-earth to, let us say, a near-Mars orbit when supply of settlements on Mars will become somewhat realistic. Cargo should be delivered to the surface of Mars in special vehicles capable of aerodynamic braking in the atmosphere and then return to orbit, i.e., playing the role of Martian MTKK.

It is probable that spacecraft with YaRD will "anchor in the roadstead" in a low near-Mars orbit without descending to the planet in order to prevent contamination of Mars with radioactive materials. Therefore, some of the calculations given above should possibly be considered as purely illustrative (this obviously does not concern expeditions to Mercury, where life is known to be impossible).

This is the possible scheme of a future interplanetary transport system, which is reasonable for that remote era when manned Earth-Mars-Earth voyages will become regular. Single-stage orbital aircraft provide an oxygen supply to the spaceport in a low near-earth orbit and assembly of single-stage interplanetary interorbital spacecraft (MMK) with YaRD in it, which make regular voyages between this orbit and the low orbit around Mars. These MMK transport people and emergency cargo, while large MMK equipped with ERD transport routine cargo for stations on Mars and oxygen and hydrogen tanks stored on a near-Mars orbital base. People and cargo are delivered from low orbit to Mars and return in Martian MTKK, which pick up oxygen and hydrogen (alas, fluorene is toxic to Mars!) at the orbital base in order to return to it (this is how they differ from terrestial MTKK based on the surface rather than in orbit). People and small cargo are returned to Earth in nuclear MMK which draw hydrogen at the orbital base.

And only during expeditions to the edges of the Solar System will it be possible, as many hope, to use oxygen extracted in the atmospheres of Jupiter type planets and on the surfaces of their satellites, rather than delivered from Earth.

Let us permit ourselves to dream just a bit more. Some specialists* express confidence that somewhere at the end of this century or the beginning of next

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*See, for example, the article of W. Kurt in the collection of reports of the American symposium of 1966 "The Space Era. Forecasts for the Year 2001" (translated into Russian, Moscow, Mir, 1970).

it will be possible to develop gas-phase YaRD, completely safe from the viewpoint of environmental contamination (a "gas-phase YaRD with transparent ampule"). Launch of a spacecraft with YaRD directly from the Earth's surface will then become possible. When an exhaust velocity of w = 50 km/s becomes a reality, the amount of working body (hydrogen) on the spacecraft will comprise not more than 20 percent of its launch mass if the purpose is to insert it into a low near-earth orbit. After orbit insertion, it is adequate to have available only the quantity of hydrogen which was expended so that the spacecraft can complete a flight to Mars and return within 972 days after launch (along Hohman trajectories). Such a spacecraft, in no way resembling present carrier rockets (they are, figuratively speaking, flying kerosene cans), will hardly differ from the spacecraft from science-fiction novels. With a large oxygen reserve, it can also get along without orbital refueling: a 150-ton single-stage spacecraft (50 tons of payload), launched from the Earth's surface, may without refueling complete a 6-year expedition with reactive orbit insertion around Saturn and additional maneuvering in its vicinity.

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